A RAND NOTE

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SHUTTLE FLEET OPERATIONS:
A SIMULATION ANALYSIS

David Leinweber

October 1984

N-1761-1-AF

Prepared for

The United States Air Force

Rand
1700 MAIN STREET
P.O. BOX 2138
SANTA MONICA, CA 90406-2138

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PREFACE

This Note is part of a series documenting Rand research on shuttle contingencies and means for coping with them. The space shuttle simulation model and analysis discussed herein should be of interest to military and civilian space planners and others concerned with the future of America's efforts in space. Other Notes in this series include N-1295-AF, *Cost Effective Measures of Replenishment Strategies for Systems of Orbital Spacecraft*, two classified Notes, and two forthcoming Reports on future payload requirements and general DoD space transportation system planning issues.

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This Note documents a two-part analysis of the reliability of the Space Transportation System (STS). The first part is a strictly statistical examination of the inherent bounds on reliability prediction based on accumulated mission experience as the shuttle program evolves. The results of this analysis suggest that it will take a long history of successes to firmly establish a high shuttle reliability, and that therefore, some contingency provisions should be retained during the early part of the program at least. The second phase of the analysis is aimed at gaining some insight into the operational consequences of less than perfect reliability. This analysis suggests that the risks from the uncertainties surrounding loss or retirement of orbiters, stand-down periods, and delays in refurbishment and turnaround can be reduced by supplementing the four-orbiter STS fleet with additional orbiters or an alternative launch system.

Additional keywords: Space missions, launch vehicles, statistical analysis, computations, confidence intervals, computerized simulation, statistical bounds.

SUMMARY AND CONCLUSIONS

We know, as of this writing, virtually nothing about the demonstrated reliability of Space Transportation System (STS). A single success tells us only that the reliability of the system is larger than zero. Even after a series of 100 successful flights, unmarred by a single failure, the strongest statistically sound* statement we can make about the reliability of the space shuttle is that it is at least 95 percent, a level comparable with our most reliable expendable launchers.

Considerable uncertainties surround other factors critical to the ability of the Space Transportation System to meet its assigned schedule of missions as the primary launch system for all U.S. space activities in the coming decade. In addition to the reliability of the system, these uncertainties include the longevity of the orbiters, the rapidity with which they can be turned around and relaunched, and the lengths of the stand downs that will follow any mishap.

This Note first examines our knowledge of shuttle reliability, i.e., what are the statistical bounds on shuttle reliability that we can infer from 10 successful missions, 100 successful missions, or any number of successful missions, both with and without failures.

The second set of issues discussed here involves the complex interactions of uncertain factors and their consequences on the operation of the shuttle fleet. The nominal mission schedule will be affected by loss of orbiters, stand-down periods, retirement of orbiters, and delays in refurbishment and turnaround. These factors

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* With 95 percent confidence.

interact in a complex way to reduce the capacity of the four-orbiter fleet below the levels projected for the system's operational period. The simulation model described in this Note was used to analyze these questions and draw conclusions regarding a more realistic estimate of the performance of the space transportation system.

The first conclusion is that it will take a long history of successes to establish firmly a high shuttle reliability. Second, improvements in reliability of between one and two orders of magnitude over expendable launch vehicle (ELV) reliability are required for the four-orbiter fleet to complete all its missions in a timely manner. Since there are not enough missions scheduled to firmly establish a statistical justification for believing in such high reliabilities, we are conducting our continuing space activities in an uncertain environment. The risks from these uncertainties can be reduced by supplementing the four-orbiter STS fleet with additional orbiters or an alternative launch system.

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I. INTRODUCTION

The analysis documented in this Note consists of two distinct parts. The first part explores the inherent bounds on reliability prediction based on accumulated mission experience as the shuttle program evolves. This analysis is purely statistical in nature and does not depend in any way on the unique aspects of the shuttle program. The reliability bounds derived would apply equally to an unknown weighted set of dice, electronic components, or any other system subject to failure. The conclusion of that analysis is that we will be well into the program before we accumulate high statistical confidence in system reliability. This suggests that some contingency provisions should be retained during at least the early part of the program unless we are willing to accept the possibility of major disruptions in our space activities. Just what these contingency provisions might be and what cost should be incurred to implement them is beyond the scope of this Note.

The second phase of the analysis is aimed at gaining some insight into the operational consequences of less than perfect reliability. A simulation analysis was performed which is driven primarily by two sets of probabilities. The first is the probability of a failure (i.e., an abnormal event capable of resulting in the loss of an orbiter and requiring a stand-down period to evaluate its cause and make any required corrections to remaining orbiters) occuring during a launch or flight. These failure events will result in abort situations. The second important parameter in the model is the probability that an orbiter will be lost following one of these abort situations. Both of these probability distributions are unknown so a wide range of plausible values was chosen for each.

The lowest value used for system reliability was one derived from the 1970 to 1980 expendable launch vehicle performance. This base value was increased by a factor of the square root of 10 applied successively four times resulting in a high case with a reliability 100 times greater than that observed for expendable launch vehicles in the last decade.

The second parameter with critical bearing on the results of the analysis is the probability of the loss of an orbiter following a failure requiring an abort. If this probability were zero, no vehicles lost would be lost in any abort situation. If this probability were taken to be one, no recovery would be possible and every abort would result in the loss of an orbiter. Clearly, neither of the extremes represents a particularly plausible case. For purposes of this Note this probability was varied within the range of 0.2 to 0.8. These choices, in conjunction with the four reliability profiles described above, span a large set of plausible values for shuttle system performance figures.

In the following section, the statistical bounds on shuttle reliability are explained in some detail. Section III describes the structure of the simulation model. Section IV gives the results of the model when applied to the spanning set of parameters described here without consideration of operational details in order to give a broad picture of the operational consequences of various levels of shuttle reliability. Section V presents conclusions based on this analysis. The appendixes contain supporting information and additional simulation runs using different data exercising additional features of the model. Appendix A details the reliability bound calculation of Sec. II, Appendix B contains the program listing for the simulation model and a demonstration run, and Appendix C contains results of simulation runs on hypothetical time-varying reliability cases looking at effects of orbiter retirement, turnaround time delay, and other factors.

II. STATISTICAL BOUNDS ON KNOWLEDGE ABOUT SHUTTLE RELIABILITY

The shuttle has been designed to far exceed the reliability demonstrated by previous launch vehicles. By following a "fail-operational" design philosophy, NASA has sought to design all critical systems to high reliabilit· ·tandards. Fully redundant and dissimilar systems are used for backup and protection against common mode failures. Crew training has emphasized safety as well [Ref. 1].

We hope that the reliability of the shuttle will far exceed the reliabilities experienced in the operations of expendable launch vehicles. From 1970 to 1980 the United States launched 277 expendable vehicles. Fifteen of these launchers were lost, implying a reliability of slightly under 95 percent. This figure is in rough agreement with an estimate of the reliability for expendable launch vehicles derived from insurance rates, since the usual premiums charged (between 5 and 10 percent of the value associated with the launch) reflect approximately the same degree of reliability. Despite our hopes, however, we will know (with high statistical confidence) that high reliability has been achieved for the shuttle only after many years of successful operations.

We can ask what can be said statistically about shuttle reliability based on a growing, successful operating experience. After one successful flight we know with certainty only that the reliability is not zero. But what can we say about the upper and lower 95 percent confidence bounds on shuttle reliability as more and more successful missions are flown? The statistical details of this problem are explained in Appendix A, but the illuminating result is shown in Fig. 1, which is a plot of the upper and lower bounds for a shuttle flying a

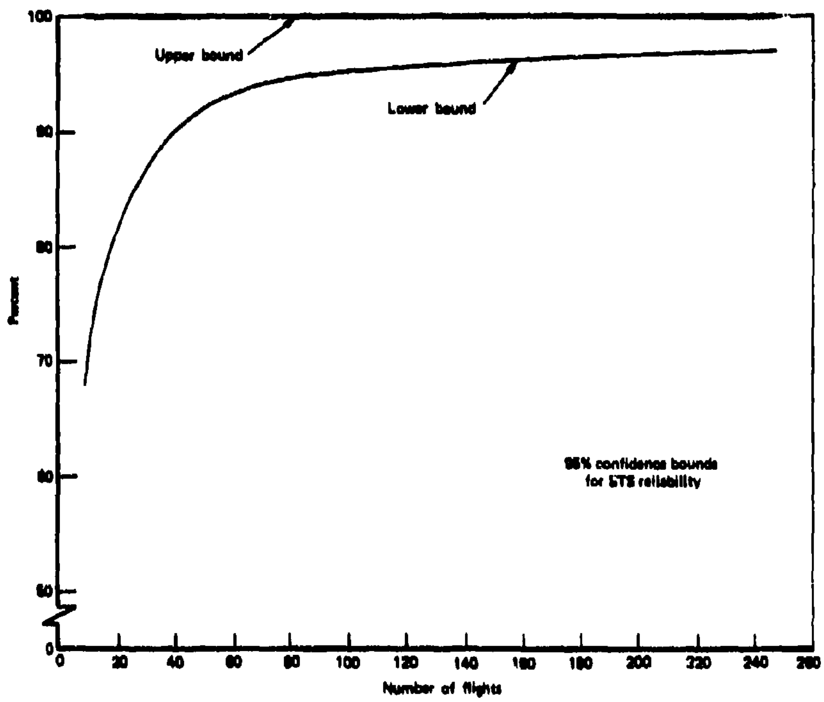

Fig. 1 — No failure reliability bounds

series of successive missions without failure. The upper bound in all of these cases is 100 percent. The lower bound rises rather slowly with increasing numbers of missions. For instance, the first 10 missions, which are not slated to have been flown until mid-1983, will establish a reliability of only 67 percent (this is, as in all reliability figures given in this discussion, with a 95 percent statistical confidence level). After 30 missions, which are expected to have been flown by the beginning of 1985, we can say only that this lower bound has increased to 87 percent. To establish a 95 percent lower bound on the reliability will require 100 missions, and to maintain with high statistical confidence that the shuttle has indeed exceeded the reliability of expendable launch vehicles by an order of magnitude (this would be a 99.5 percent reliability, reflecting a reduction in the failure rate from 5 percent to 0.5 percent) will require over 1000 missions without a failure--more than twice as many missions than are planned for the entire shuttle fleet during its lifetime. Thus, we will always be operating in a realm of considerable uncertainty regarding the reliability we can expect for the shuttle.

In determining the confidence bounds on shuttle reliability, the preceding discussion has assumed that there are no failures. A single failure at some point during the operation of the STS fleet drops the lower bound substantially, as seen in Fig. 2. A single failure in 20 flights, for example, will leave the upper confidence limit at 100 percent, but will drop the lower bound on the reliability from 82 percent in the no-failure case to approximately 74 percent. Table 1, which shows values taken from both of these curves, illustrates the drop in the lower confidence bound caused by a single failure.

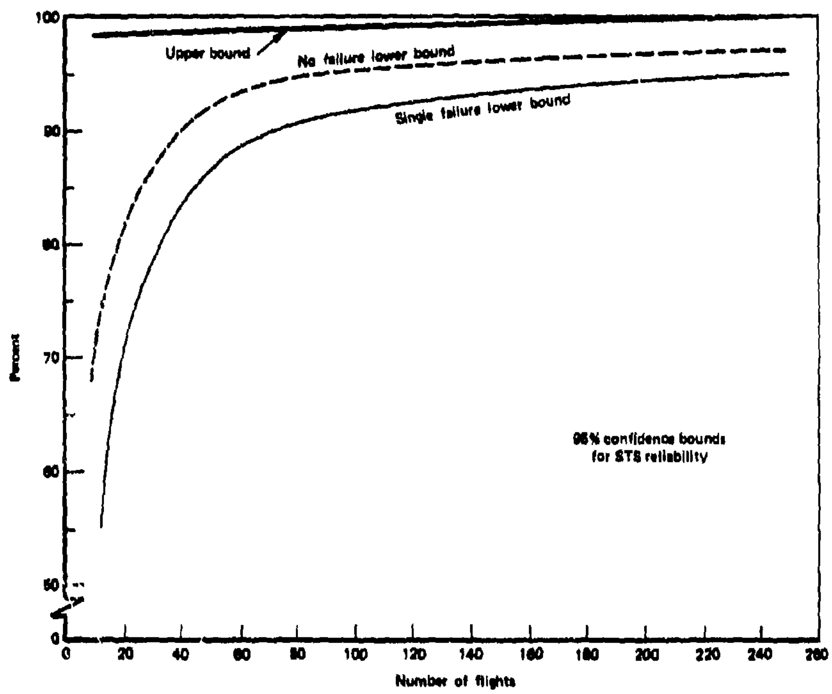

Fig. 2 — Single failure reliability bounds

Table 1

NO FAILURE AND SINGLE FAILURE LOWER RELIABILITY BOUNDS

(95 percent statistical confidence)

Number of Missions	No Failure Lower Bound	Single Failure Lower Bound
10	68%	55%
15	77%	68%
20	82%	74%
30	87%	83%
50	92%	88%
100	95%	91%
250	97%	95%

III. THE SPACE TRANSPORTATION SYSTEM SIMULATION MODEL

The primary structure of the STS simulation model is seen in Fig. 3. The simulation starts at the point labeled A, and proceeds until all missions are flown or no orbiters are available to fly them. On each iteration an orbiter is selected from those still available (i.e., not lost to accident or retired) and assigned to a launch. A simulated turnaround interval is generated to allow for possible delays in the refurbishment of the orbiter and preparation for launch. When this delay period, drawn from a uniform distribution*, has elapsed, the launch and normal mission activities commence. The probability of a normal successful recovery of the orbiter is determined from the reliability curves in Sec. I, dependent on the number of missions the orbiter in question has already flown.

When the Monte Carlo simulation results in a successful flight, the orbiter is credited with an additional mission, and if this brings its lifetime mission total up to the retirement standard, the orbiter is retired and taken out of service. Otherwise it is returned to the available pool. If an abort situation occurs, an additional Monte Carlo decision is made on whether it will be successful or result in the loss of an orbiter.** In either case, a stand down of the entire fleet follows. Its length is drawn from a uniform distribution dependent on the severity of the failure and the number of orbiters remaining that

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* The distribution for the turnaround time delays depends only on the specified average delay. It is uniform from zero to twice the average value.

** For all cases shown in this Note, the probability of successful recovery following an abort is varied from 0.2 to 0.8.

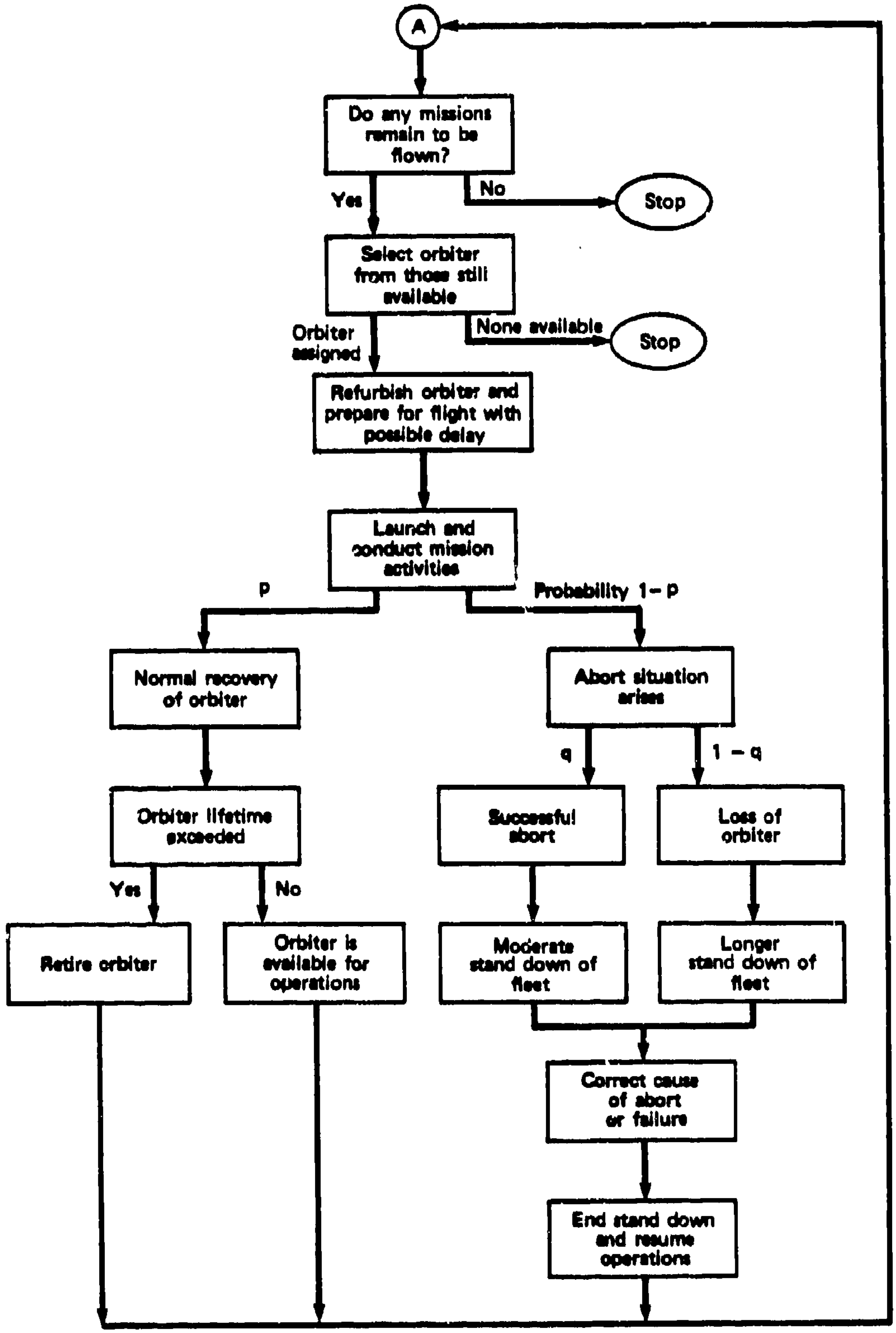

Fig. 3 — Model structure

require correction. After the stand-down interval* has elapsed, operations resume as before.

This model captures many of the uncertain aspects of shuttle operations, such as time-varying reliability, turnaround time delays, aborted missions, stand downs for repair, and the retirement or loss of orbiters. The detailed specification of the model and its computer program listing are found in Appendix B.

The basic runs described in the following sections do not include the level of detail the model is capable of handling. Since these runs are based on very broad order-of-magnitude changes in reliability over ELVs, it does not make sense to consider the intricacies of the cases in great detail. A second set of simulation runs using hypothetical time-varying reliabilities is found in Appendix C.

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* The stand-down is a random variable that depends on the severity of the failure (loss/no loss) and the number of orbiters left. The stand-down time in weeks, S, is given by S=S1+R(L/4) where S1 is 20 for a no-loss failure and 30 for a lost orbiter failure. L is the number of orbiters remaining, and R is a uniformly distributed random variable in [0,1].

IV. RESULTS OF THE SIMULATION

Figure 4 shows the reliability profiles for the base cases used in the simulation analysis. These reliables are constant over the entire life of the orbiter, showing no learning and no wearout. For these simulations it was assumed that no retirement of orbiters would be required and if necessary any one would be capable of flying the entire 312 missions. In practice, because of the high reliabilities involved, this situation will almost never occur. The bottom line in Fig. 4 at 0.95 represents the observed reliability of expendable launch vehicles during the period 1970 to 1980. Of 277 launches during that decade, 15 resulted in failures. This value of 0.95 is not particularly interesting as a basis for simulation of shuttle operations because, first, it is almost certain the shuttle will achieve substantial improvements over ELV reliabilities and, second, the 0.95 value is sufficiently low that very few missions would be flown before all four orbiters were lost. This is due to the repeated exposure of each of the orbiters to the risk of 0.95, resulting eventually in the near certainty of a loss. The first case represents an improvement over the ELV reliability level by a factor of the square root of 10, approximately 3.17. This results in a constant reliability of 0.984, the first reliability case. Applying this factor again results in a constant reliability of 0.995, an order of magnitude improvement over ELVs. Another application of the factor results in 0.9984, and the final application results in a reliability of 0.9995, an improvement of two orders of magnitude over ELVs. These are the four reliability cases

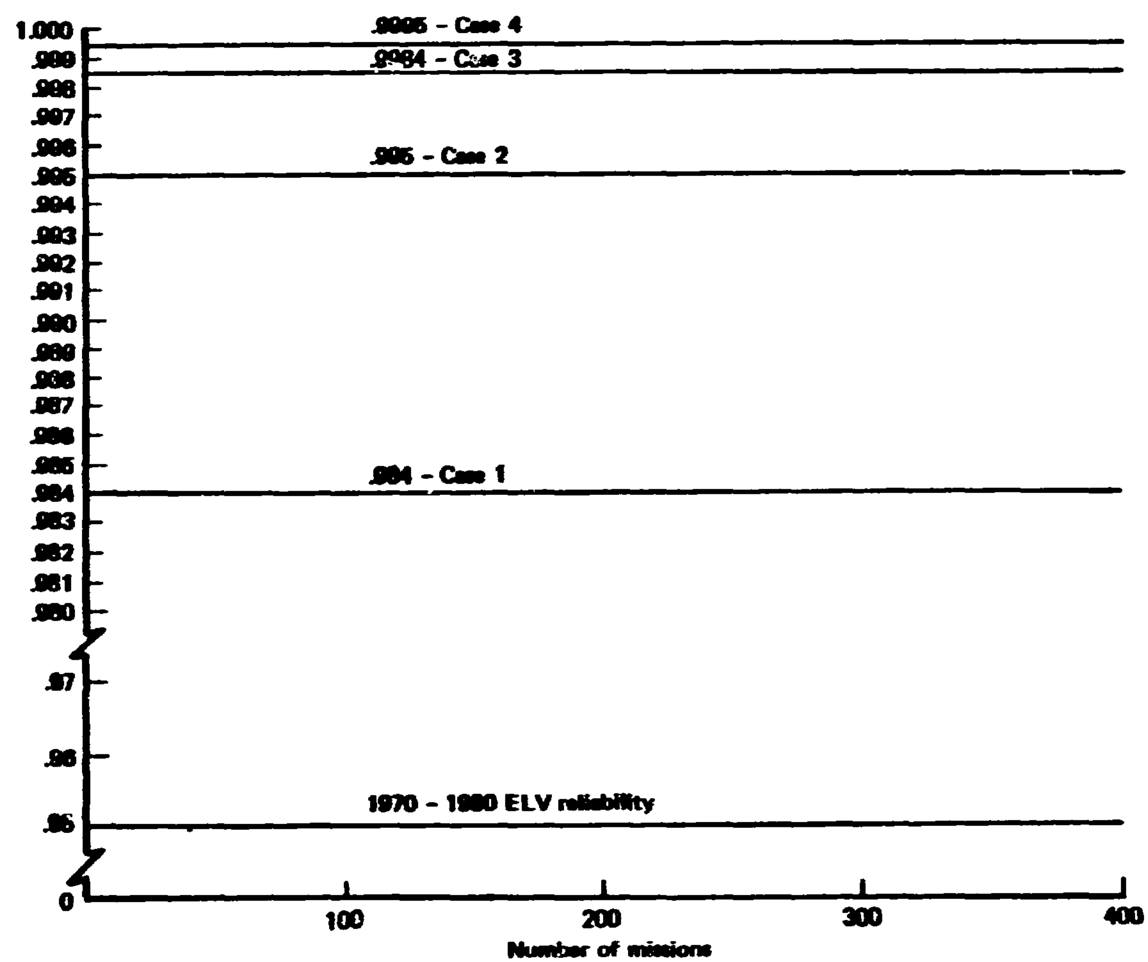


Fig. 4 — Base Cases 1–4 reliability constant, increasing by factors of $\sqrt{10}$ over ELVs;
No learning–no wearout

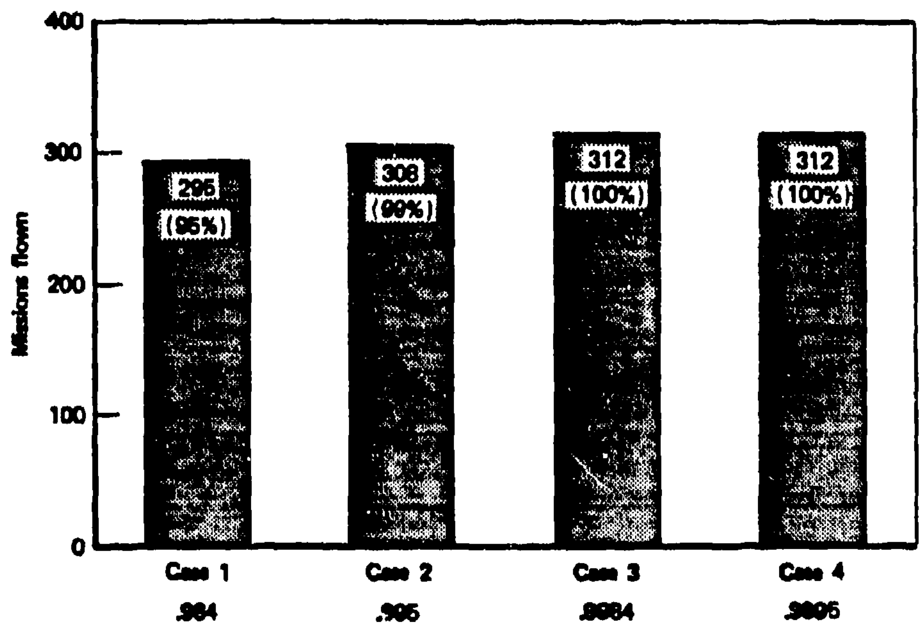


Fig. 5 — Missions flown (for q = .3)

used for this simulation.

The scheduled mission sequence for the simulation consists of 312 flights over a period of six years (for a nominal rate of one flight a week). As seen in Fig. 5, in all four cases at least 95 percent of the missions were flown, even for the relatively pessimistic assumption of q=0.3 (i.e., the probability of recovery of an orbiter following an abort is 30 percent). In the lower reliability cases, Cases 1 and 2, additional flights were flown by the remaining orbiters in order to make up any shortfall due to a loss. However, even in the worst simulated case the maximum number of missions per orbiter did not exceed 114.

The number of orbiter losses depends strongly on the probability of loss following a failure resulting in an in-flight abort. Since this parameter cannot be known with any certainty, it was varied over the "plausible" range of 0.2 to 0.8. Values above this begin to result in orbiters with "charmed lives," which cannot be lost in any accident, and those with values below this range represent extemely lost-prone vehicles, which are only rarely recovered following a failure. Figure 6 shows the expected values for orbiter losses versus the probability of loss in each of the four cases considered. It is seen that this parameter plays less and less of a role in the performance of the fleet in the higher reliability cases. This is to be expected since it has an effect only once a failure has occurred and when the probability of a failure as represented by the four reliability base cases is so low that these branches of the event tree are rarely traversed.

In this section we have related in a broad-stroke way the operational performance measures of missions flown and orbiters lost to

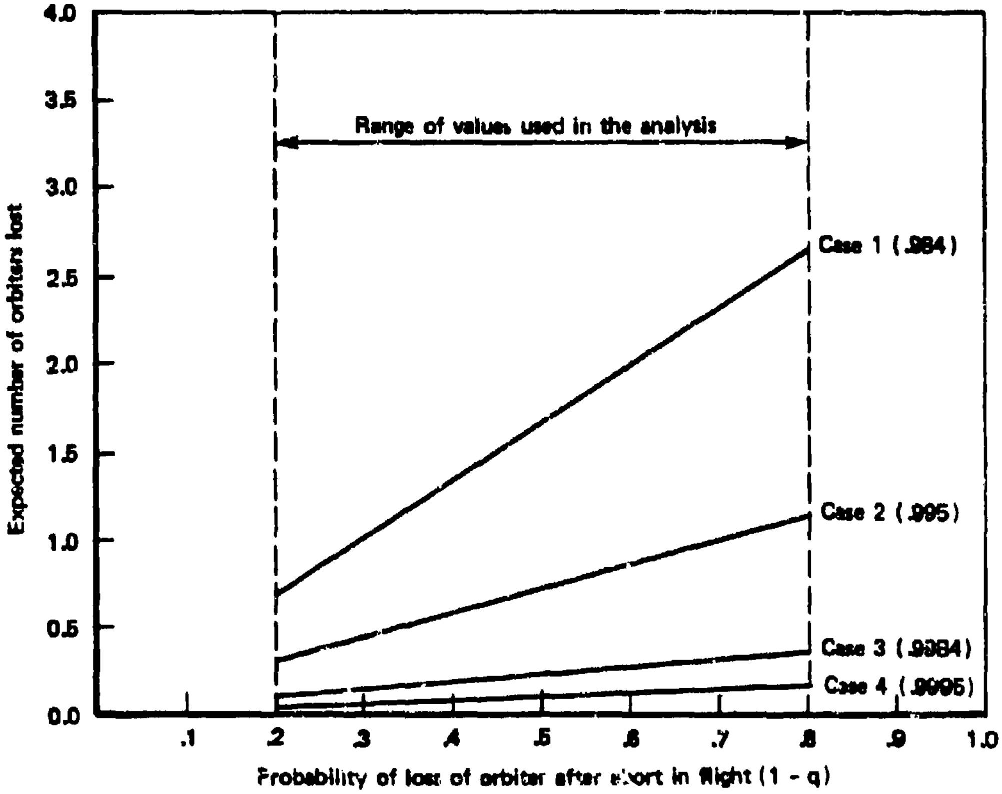


Fig. 6 — Expected orbiter losses versus probability of loss
(312 missions)

the abstract reliability parameters that drive the model. The upper ranges of reliability, Case 2 and beyond, have excellent fleet performance with 99 percent or more of the missions being fown and expected orbiter losses of one vehicle or less. If in fact the actual orbiter reliabilities are equal to or greater than these values, i.e., 10 times better than ELVs, the performance of the actual fleet can be expected to be close to that described here. However, if a number of failures in the early history of the program is sufficiently high, then, based on the discussion in Sec. II, we can conclude that it is unlikely that the actual orbiter reliability is in the upper ranges, and some means for supplemental access to space looks more desirable.

APPENDIX A: CALCULATION OF CONFIDENCE INTERVALS FOR SHUTTLE RELIABILITY

Determination of the confidence bounds for shuttle reliability given in Sec. I was based on the method described in Ref. 3. For the no-failure case, the usual statistical techniques, based on sample values, are inadequate, since the sample standard deviations are all zero. Clopper and Pearson solve the problem by graphical construction, and the reader can use their results, seen in Figs. A-1 and A-2, to determine the confidence bounds on shuttle reliability for cases not included in Sec. I.

Figure A-1, for determination of 95 percent confidence intervals, was used to generate the plots of Figs. 1 and 2. Figure A-2, for 99 percent confidence intervals, was not used. As expected, the 99 percent intervals are larger (i.e., have more pessimistic lower bounds) than the 95 percent intervals.

To find either 95 or 99 percent confidence intervals, select the appropriate figure and determine the position on the horizontal axis by calculating the fraction of successful missions for the case of interest; for example, 5 failures in 50 missions give a value for x/n of 0.90. Looking up along $x/N=0.9$ on Fig. A-1 to the intercepts for $N=50$, one reads 95 percent confidence level reliability bounds of 77 percent and 96 percent. The 99 percent confidence level bounds are found in the same fashion, using Fig. A-2, to be 74 to 97 percent.

This method can be used at any point in the ongoing operation of the STS fleet to determine how strong a statistical statement can be made regarding shuttle reliability based on the historical performance of the fleet.

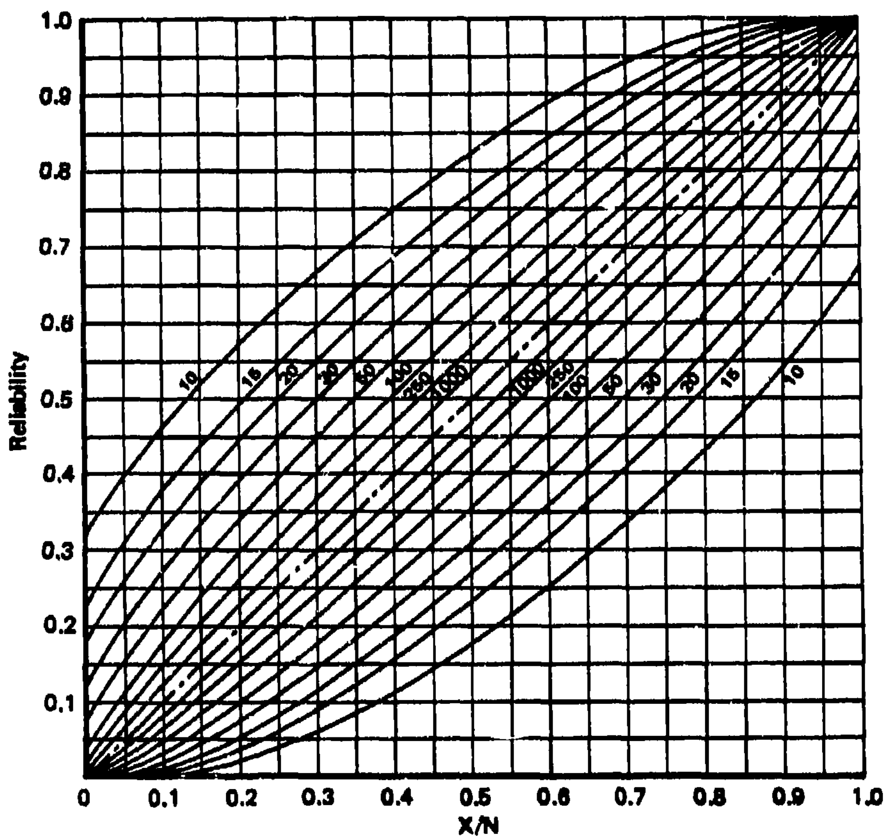


Fig. A-1 — 95% confidence bounds on shuttle reliability

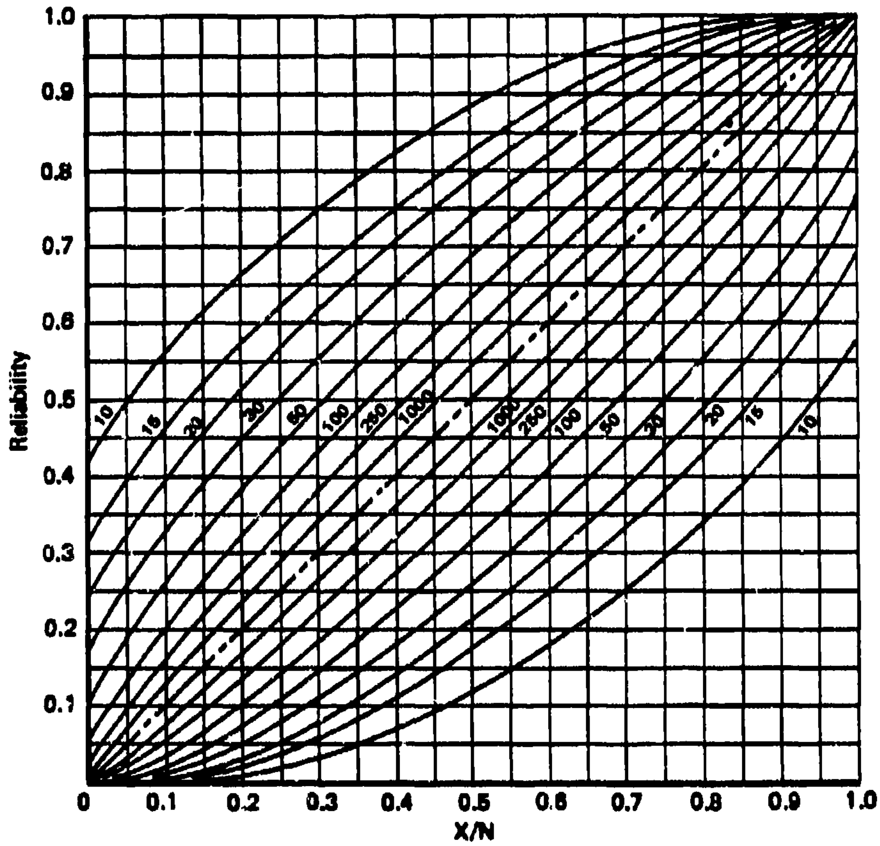


Fig. A-2 — 99% confidence bounds on shuttle reliability

APPENDIX B: ANNOTATED MODEL LISTING AND SAMPLE RUN

The simulation model was coded in PASCAL and run on an Apple II computer with 48K of memory. It was constructed in a modular, structured fashion, with the main simulation loop operating as shown in Fig. 3. The subroutines and functions used are described below.

SELECTORB: Picks the available orbiter with the fewest flights for the next mission.

RAND: Returns a random number uniformly distributed between 0 and 1.

INIT: Initializes parameters used for the entire simulation (all four reliability cases) and initializes all statistical accumulators to zero.

SETUP: Initializes those parameters required for the particular reliability case being simulated. Sets the quadratic fit to determine reliability for an arbitrary mission based on the parameters in Table 2. Plots these reliability curves on the first iteration for each reliability case.

CASEOUT: Prints a brief table showing the status of each orbiter after a single simulation run for each reliability case.

STATLOG: Accumulates the values needed to generate statistics for the collection of 50 runs of each of four cases.

STATOUT: Writes the summary table after all runs are completed. These tables are seen in Tables 6 through 11 of this Note.

STAT2: Called by STATOUT to compute and write the numerical results under the headers written by STATOUT. This is separate from STATOUT because of size restrictions imposed by the compiler.

The following pages contain the listing and output for the simulator run with an average delay of 60 percent and orbiter retirement after 120 flights. Because of the volume of the output, only the first and last few individual runs are shown.

MODEL LISTING

```
 1    1:D     1 (*$L REMOUT:*)
 1    1:D     1 (*$G+*)
 1    1:D     1 PROGRAM SIM;
29    1:D     3
29    2:D     3   FUNCTION SIN(X:REAL):REAL;
29    3:D     3   FUNCTION COS(X:REAL):REAL;
29    4:D     3   FUNCTION EXP(X:REAL):REAL;
29    5:D     3   FUNCTION ATAN(X:REAL):REAL;
29    6:D     3   FUNCTION LN(X:REAL):REAL;
29    7:D     3   FUNCTION LOG(X:REAL):REAL;
29    8:D     3   FUNCTION SQRT(X:REAL):REAL;
29    8:D     5
22    1:D     5
22    1:D     3
22    2:D     3     FUNCTION PADDLE(SELECT: INTEGER): INTEGER;
22    3:D     3     FUNCTION BUTTON(SELECT: INTEGER): BOOLEAN;
22    4:D     1     PROCEDURE TTLOUT(SELECT: INTEGER; DATA: BOOLEAN);
22    5:D     3     FUNCTION KEYPRESS: BOOLEAN;
22    6:D     3     FUNCTION RANDOM: INTEGER;
22    7:D     1     PROCEDURE RANDOMIZE;
22    8:D     1     PROCEDURE NOTE(PITCH,DURATION: INTEGER);
22    8:D     3
 1    1:D     3 USES TRANSCEND,APPLESTUFF;
 1    1:D     3 LABEL 1;
 1    1:D     3 VAR ITER,I1,I2,IO,ICASE,K,MAXMISS,NMISS,NORB,ORBLEFT,NRUNS: INTEGER;
 1    1:D    14
 1    1:D    14  S,T,DELAY,M,R1,RM,RN,N,N2,M2,A,B,C,S1: REAL;
 1    1:D    42  D,D1,D2,D3,REL: REAL;
 1    1:D    52  ORB,ORBFL:ARRAY [1..4] OF INTEGER;
 1    1:D    60
 1    1:D    60  R: ARRAY [1..5] OF ARRAY [1..4] OF REAL;
 1    1:D   100  MF,TC,OL,MO,MM: ARRAY [1..4] OF ARRAY [1..2] OF REAL;
 1    1:D   180  (* MISSIIONS FLOWN, TIME TO COMPLETION, ORBITERS
 1    1:D   180  LOST, MISSIONS PER ORBITER, MAX MISS. PER ORB. - SUMS AND SUMS OF SQUARES *)
 1    1:D   180
 1    1:D   180  CT: STRING;
 1    1:D   221
 1    1:D   221
 1    2:D     3     FUNCTION SELECTORB: INTEGER;
 1    2:D     3    (* CHOOSE ORBITER WITH FEWEST FLIGHTS*)
 1    2:D     3    VAR L,FMIN: INTEGER;
 1    2:0     0    BEGIN
 1    2:0     0
 1    2:1     0    FMIN:=500;
 1    2:1     5    FOR L:=1 TO 4 DO  BEGIN
 1    2:3    16         IF (ORB[L]>=0) AND (ORB[L]<FMIN) THEN FMIN:=ORB[L];
 1    2:2    58         END;
 1    2:1    65    FOR L:=1 TO 4 DO  BEGIN
 1    2:3    76         IF ORB[L]=FMIN THEN SELECTORB:=L;
 1    2:2    94         END;
 1    2:0   101   END;
 1    2:0   118
 1    3:D     3    FUNCTION RAND:REAL;
 1    3:0     0    BEGIN
 1    3:1     0    RAND:=RANDOM/32767;
 1    3:1    15
 1    3:0    15    END;
 1    3:0    28
 1    3:0    28
 1    3:0    28
 1    3:0    28
 1    3:0    28
 1    4:D     1  PROCEDURE INIT;
 1    4:0     0  BEGIN
 1    4:0     0
 1    4:1     0  NRUNS:=50;
 1    4:1     3
 1    4:1     3    (*R[I,J]: J= CASE TYPE, I= PARAMETER
 1    4:1     3    R[1,J]=R(1)
 1    4:1     3    R[2,J]=M
 1    4:1     3    R[3,J]=R(M)
 1    4:1     3    R[4,J]=R(120)-COMPUTED-
 1    4:1     3    R[5,J]=MAX.MISS.PER ORB. *)
 1    4:1     3
 1    4:1     3 R[1,1]:=0.995;
 1    4:1    30 R[1,2]:=0.99;
 1    4:1    56 R[1,3]:=0.97;
 1    4:1    82 R[1,4]:=0.995;
 1    4:1   108
 1    4:1   108 R[2,1]:=45.0;
 1    4:1   134 R[2,2]:=60.0;
 1    4:1   160 R[2,3]:=60.0;
 1    4:1   186 R[2,4]:=60.0;
 1    4:1   212
 1    4:1   212 R[3,1]:=0.9985;
```

```
1    4:1    238 R[3,2]:=0.998;
1    4:1    264 R[3,3]:=0.99;
1    4:1    290 R[3,4]:=0.998;
1    4:1    316
1    4:1    316    (* R4 COMPUTED *)
1    4:1    316
1    4:1    316 R[5,1]:=120.0;
1    4:1    342 R[5,2]:=120.0;
1    4:1    368 R[5,3]:=120.0;
1    4:1    394 R[5,4]:=120.0;
1    4:1    420
1    4:1    420 DELAY:=2.0;
1    4:1    430
1    4:1    430 FOR I1:=1 TO 4 DO
1    4:2    441   FOR I2:= 1 TO 2 DO
1    4:3    452     BEGIN
1    4:4    452     MF[I1,I2]:=0.0;
1    4:4    480     TC[I1,I2]:=0.0;
1    4:4    508     OL[I1,I2]:=0.0;
1    4:4    536     MO[I1,I2]:=0.0;
1    4:4    562     MM[I1,I2]:=0.0;
1    4:3    588     END;
1    4:3    602
1    4:3    602
1    4:3    602
1    4:1    602 CT:='TYPE   R(1)     M      R(M)        MAX.MISS';
1    4:1    650 N:=120.0;
1    4:1    660 N2:=120.0*120.0;
1    4:1    677 WRITELN;
1    4:1    685 WRITELN('RAND STS RELIABILITY SIMULATION');
1    4:1    736 WRITELN; WRITELN;
1    4:1    752
1    4:0    752 END; (*INIT*)
1    4:0    772
1    5:D      1 PROCEDURE SETUP;
1    5:0      0 BEGIN
1    5:1      0 RANDOMIZE;
1    5:1      3 ORBLEFT:=4;
1    5:1      6
1    5:1      6 FOR I1:=1 TO 4 DO
1    5:2     17 BEGIN
1    5:2     17
1    5:3     17 ORB[I1]:=1;
1    5:3     29 ORBFL[I1]:=0;
1    5:2     41 END;
1    5:2     48
1    5:2     48
1    5:2     48 (* ORB ARRAYS  SET *)
1    5:2     48
1    5:2     48
1    5:1     48 NMISS:=0;
1    5:1     51 T:=0;
1    5:1     57 S:=0;
1    5:1     63 MAXMISS:=4*TRUNC(R[5,ICASE]);
1    5:1     89 IF MAXMISS>480 THEN MAXMISS:=480;
1    5:1    101 R1:=R[1,ICASE] ;
1    5:1    125 M:=R[2,ICASE] ;
1    5:1    149 RM:=R[3,ICASE] ;
1    5:1    173
1    5:1    173 M2:=M*M;
1    5:1    186 WRITELN; WRITELN;
1    5:1    202 WRITELN('CASE TYPE ',ICASE,' RUN ',ITER);
1    5:1    269 WRITELN(R[1,ICASE],'  ',R[2,ICASE],'  ',R[3,ICASE],'  ',
1    5:1    401          '  ',R[5,ICASE]);
1    5:1    453
1    5:1    453 WRITELN(' ');WRITELN(' ');
1    5:1    489 A:=(R1-RM)/M2;
1    5:1    507 B:=-2.0*(R1-RM)/M;
1    5:1    534 C:=R1;
1    5:1    542
1    5:1    542
1    5:1    542
1    5:1    542 IF ITER=1 THEN (* PRINT/PLOT RELIBILITY FIRST TIME *)
1    5:1    547
1    5:2    547  BEGIN
1    5:3    547   WRITELN;
1    5:3    555   FOR I1:=0 TO 10 DO WRITE('        ',90-I1,'%');
1    5:3    614   WRITELN;
1    5:3    622   FOR I1:=0 TO 10 DO WRITE('---------!');
1    5:3    662   WRITELN;
1    5:3    670   FOR I1:=1 TO ROUND(R[5,ICASE]/5.0)+5 DO BEGIN
1    5:5    712   K:=I1*5;
1    5:5    717   REL :=K*(A*K + B) + C;
1    5:5    741   IF REL>1.0 THEN REL:=1.0;
1    5:5    766   WRITELN;
```

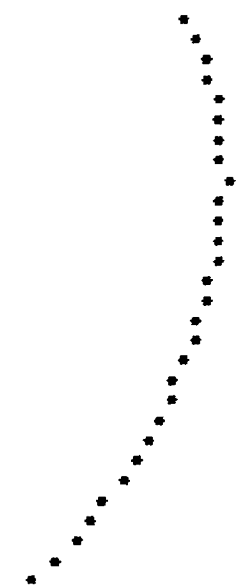
```
1    5:5   774    WRITE(K,'    ',REL   );
1    5:5   813    IF REL<0.9 THEN REL:=0.9; (* FOR PLOT ONLY *)
1    5:5   838
1    5:5   838    FOR I2:=1 TO ROUND((REL-0.9)*1000.0)-5  DO WRITE(' ');
1    5:5   889    WRITE('*');
1    5:4   899    END;
1    5:4   906
1    5:3   906   WRITELN;
1    5:2   914   END;
1    5:0   914  END; (*SETUP*)
1    5:0   940
1    6:D     1  PROCEDURE CASEOUT;
1    6:0     0      BEGIN
1    6:1     0       WRITELN(' ');
1    6:1    18         WRITELN(' ORBITER  NO. OF FLIGHTS');
1    6:1    62         FOR NORB:=1 TO 4 DO
1    6:2    73           BEGIN
1    6:3    73           IF ORB[NORB]>0 THEN
1    6:4    88              WRITELN('  ',NORB,'              ',ORB[NORB]-1)
1    6:3   164                          ELSE IF ORB[NORB]=-1 THEN
1    6:5   182              WRITELN('X ',NORB,'             ',ORBFL[NORB])
1    6:4   256                          ELSE IF ORB[NORB]=-2 THEN
1    6:6   274              WRITELN('R ',NORB,'             ',ORBFL[NORB]);
1    6:6   348
1    6:2   348           END;
1    6:2   355
1    6:1   355         WRITELN('END CASE ',ICASE);
1    6:1   394
1    6:0   394   END; (*CASEOUT*)
1    6:0   412
1    6:0   412
1    7:D     1  PROCEDURE STATLOG;
1    7:D     1   VAR NL,XT,XN:REAL;
1    7:0     0   BEGIN
1    7:1     0   XN:=NMISS;
1    7:1     6   XT:=T;
1    7:1    14   MF[ICASE,1]:=MF[ICASE,1] + NMISS;
1    7:1    59   MF[ICASE,2]:=MF[ICASE,2] + SQR(XN);
1    7:1   107   TC[ICASE,1]:=TC[ICASE,1] + T;
1    7:1   154   TC[ICASE,2]:=TC[ICASE,2] + SQR(XT);
1    7:1   202   NL:=0.0;
1    7:1   212   FOR IO:=1 TO 4 DO IF ORB[IO]=-1 THEN NL:=NL+1;
1    7:1   257   OL[ICASE,1]:=OL[ICASE,1] + NL;
1    7:1   304   OL[ICASE,2]:=OL[ICASE,2] + NL*NL;
1    7:1   356   NL:=0.0;
1    7:1   366   FOR IO:=1 TO 4 DO
1    7:2   377     IF ORB[IO]>0 THEN NL:=NL+ORB[IO]-1
1    7:2   411                  ELSE NL:=NL+ORBFL[IO];
1    7:2   446
1    7:1   446  NL:=NL/4.0;
1    7:1   461  MO[ICASE,1]:=MO[ICASE,1] + NL;
1    7:1   506  MO[ICASE,2]:=MO[ICASE,2] + NL*NL;
1    7:1   556
1    7:1   556  NL:=0.0;
1    7:1   566  FOR IO:=1 TO 4 DO BEGIN
1    7:3   577    IF NL<ORB[IO] THEN NL:=ORB[IO];
1    7:3   613    IF NL<ORBFL[IO] THEN NL:=ORBFL[IO];
1    7:2   649    END;
1    7:2   656
1    7:1   656  MM[ICASE,1]:=MM[ICASE,1] + NL;
1    7:1   701  MM[ICASE,2]:=MM[ICASE,2] + SQR(NL);
1    7:1   747
1    7:0   747  END; (*STATLOG *)
1    7:0   766
1    8:D     1  PROCEDURE STATOUT;
1    8:D     1  VAR X1,X2,X3,X4,X5,Y1,Y2,Y3,Y4,Y5:REAL;
1    8:D    21      Q:STRING;
1    8:D    62
1    8:D    62
1    9:D     1  PROCEDURE STAT2;
1    9:0     0  BEGIN
1    9:0     0
1    9:1     0  FOR ICASE:=1 TO 4 DO
1    9:2    11   BEGIN
1    9:3    11   X1:=MF[ICASE,1]/NRUNS;
1    9:3    40   X2:=TC[ICASE,1]/NRUNS;
1    9:3    69   X3:=OL[ICASE,1]/NRUNS;
1    9:3    98   X4:=MO[ICASE,1]/NRUNS;
1    9:3   126   X5:=MM[ICASE,1]/NRUNS;
1    9:3   154   WRITELN(ICASE,Q,X1,Q,X2,Q,X3,Q,X4,Q,X5);
1    9:3   307
1    9:3   307   (* CALCULATE STD. DEV. *)
1    9:3   307   Y1:=(MF[ICASE,2]/NRUNS) -X1*X1;
1    9:3   348   Y2:=(TC[ICASE,2]/NRUNS) -X2*X2;
1    9:3   389   Y3:=(OL[ICASE,2]/NRUNS) -X3*X3;
1    9:3   430   Y4:=(MO[ICASE,2]/NRUNS) -X4*X4;
```

```
1    9:3   470  Y5:=(MM[ICASE,2]/NRUNS) -X5*X5;
1    9:3   510  Y1:=SQRT(Y1);
1    9:3   525  Y2:=SQRT(Y2);
1    9:3   540  Y3:=SQRT(Y3);
1    9:3   555  Y4:=SQRT(Y4);
1    9:3   570  Y5:=SQRT(Y5);
1    9:3   585  WRITELN('  ',Q,Y1,Q,Y2,Q,Y3,Q,Y4,Q,Y5);
1    9:3   742  WRITELN;
1    9:2   750  END;
1    9:0   757 END; (* STAT2   *)
1    8:0     0 BEGIN
1    8:0     0
1    8:1     0     Q:='     ';
1    8:1    11 WRITELN; WRITELN;
1    8:1    27 WRITELN(' STATISTICS FOR ', NRUNS, ' RUNS');
1    8:1    90 WRITELN(' CASES');
1    8:1   116 WRITELN(CT);
1    8:1   136 FOR ICASE:=1 TO 4 DO WRITELN(ICASE,' ',R[1,ICASE],' ',R[2,ICASE],
1    8:2   238     ' ',R[3,ICASE],' ',' ',R[5,ICASE]);
1    8:1   343 WRITELN;
1    8:1   351 WRITELN('CASE      MISSIONS   TIME TO     ORBITERS     MISSIONS     MAX MSNS.');
1    8:1   437 WRITELN('            FLOWN     COMPLETE      LOST       PER ORB.     PER ORB.');
1    8:1   522 WRITELN;
1    8:1   530 STAT2; (* WRITE NUMERICAL OUTPUT *)
1    8:0   532 END; (* STATOUT *)
1    8:0   548
1    8:0   548
1    1:0     0 BEGIN (*MAIN PROG *)
1    1:1     0 CLOSE(OUTPUT);
1    1:1    17 REWRITE(OUTPUT,'REMOUT:');
1    1:1    37 INIT;
1    1:1    39
1    1:1    39
1    1:1    39
1    1:1    39 (* ITERATE FOR NRUNS RUNS *)
1    1:1    39 FOR ITER:=1 TO NRUNS DO
1    1:2    53 BEGIN
1    1:2    53
1    1:3    53 FOR ICASE:=1 TO 4 DO (*CASE LOOP*)
1    1:4    67 BEGIN
1    1:5    67 SETUP; (* SET INITIAL COND *)
1    1:5    69
1    1:5    69 (* INITIALIZE AND RUN MONTE CARLO SIMULATION *)
1    1:5    69 (* IF ORBITER L IS AVAILABLE THEN ORB(L)=K,
1    1:5    69    THE NUMBER OF THE NEXT MISSION, ELSE ORB(L)=-1
1    1:5    69    IF ORB FAILED, ORB[L]=-2 IF ORB RETIRED *)
1    1:5    69
1    1:5    69 (* MAIN SIM LOOP *)
1    1:5    69 WHILE NMISS<=MAXMISS DO BEGIN
1    1:7    74   IF NMISS=MAXMISS THEN BEGIN
1    1:9    79        WRITELN('MAXIMUM ',MAXMISS,' MISSIONS AT T= ',T);
1    1:9   159        GOTO 1;
1    1:8   161        END;
1    1:7   161   T:=T+1;
1    1:7   172   IF (ORBLEFT=1) AND (S=0) THEN T:=T+1; (* NO ONE WEEK TURNAROUND *)
1    1:7   197   IF (ORB[1] <0) AND
1    1:7   210      (ORB[2] <0) AND
1    1:7   224      (ORB[3] <0) AND
1    1:7   238      (ORB[4] <0) THEN BEGIN
1    1:9   254        WRITELM('ALL ORBITERS LOST OR RETIRED AT T= ',T);
1    1:9   323        WRITELN(NMISS, ' MISSIONS FLOWN');
1    1:9   368        GOTO 1;
1    1:8   370        END;
1    1:8   370
1    1:8   370 (*STANDDOWN*)
1    1:7   370 IF S>0 THEN BEGIN
1    1:9   380   S:=S-1;
1    1:8   391   END
1    1:7   391        ELSE BEGIN
1    1:9   393   NORB:=SELECTORB;
1    1:9   399   T:=T+ DELAY*RAND; (* RANDOM DELAY, UNI. DISTR FROM 0 TO DELAY*)
1    1:9   417   K:=ORB[NORB];
1    1:9   430   IF RAND>(K*(A*K + B) + C) (* FAILURE *)
1    1:9   454        THEN BEGIN
1    1:9   458
1    1:1   458          WRITELN('** FAILURE, ORBITER ',NORB, ' AT  T= ',T,' **');
1    1:1   557
1    1:1   557          IF RAND>0.7 THEN BEGIN
1    1:3   572            WRITELN('** SUCCESSFUL ABORT **');
1    1:3   614            S:=20.0;
1    1:2   624            END
1    1:1   624                       ELSE BEGIN
1    1:1   626
1    1:3   626            WRITELN('** ORBITER LOST **');
1    1:3   664            S:=30.0;
1    1:3   674            ORBLEFT:=ORBLEFT-1;
```

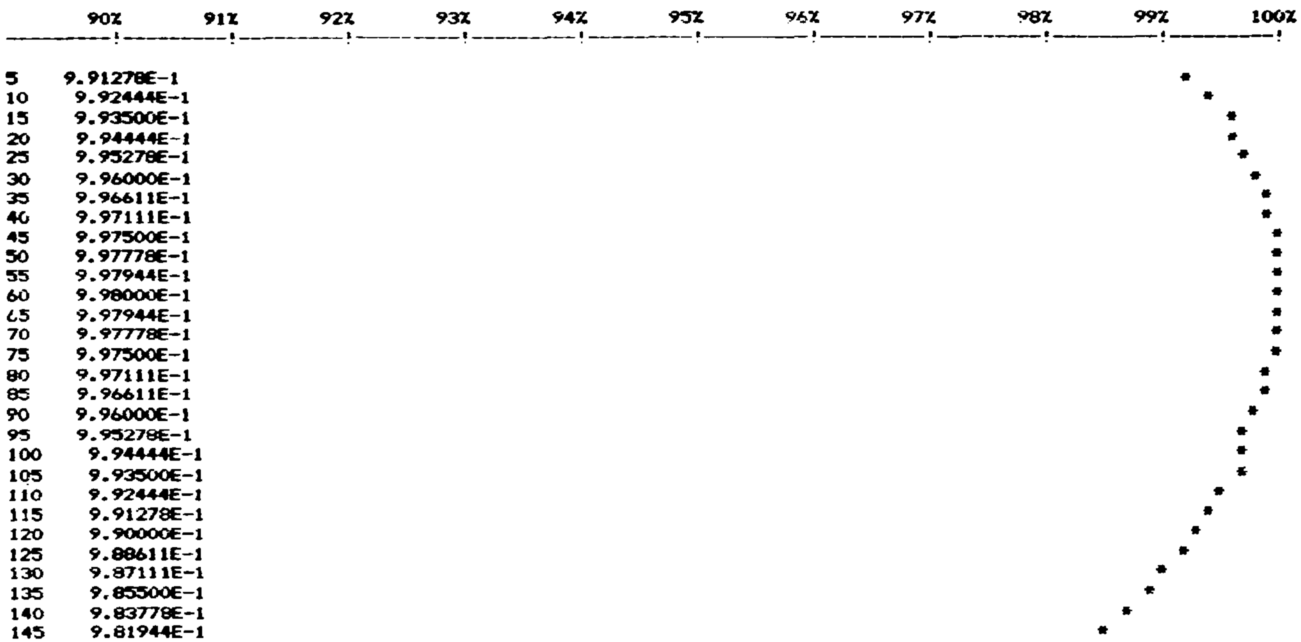
```
 1   1:3   679           ORBFL[NORB]:=ORB[NORB]; (*LOG NO. OF FLIGHTS *)
 1   1:3   701           ORB[NORB]:=-1;
 1   1:2   714           END;
 1   1:2   714
 1   1:1   714         S:=S1 + RAND*4( .0*(ORBLEFT/4); (* VAR. STANDOWN *)
 1   1:1   740         WRITELN('** STANDOWN LENGTH: ',ROUND(S));
 1   1:0   795        END
 1   1:0   795
 1   1:9   795       ELSE BEGIN  (* SUCCESS *)
 1   1:1   797         NMISS:=NMISS+1;
 1   1:1   802         ORB[NORB]:=ORB[NORB]+1;
 1   1:1   826         IF ORB[NORB]=R[5,ICASE]+1  THEN (* RETIRE ORBITER *)
 1   1:2   865           BEGIN
 1   1:3   865           ORB[NORB]:=-2;
 1   1:3   878           WRITELN('-- ORBITER ',NORB,' RETIRED AT T= ',T,' --');
 1   1:3   975           ORBFL[NORB]:=TRUNC(R[5,ICASE]);
 1   1:3  1008           ORBLEFT:=ORBLEFT - 1;
 1   1:2  1013           END;
 1   1:2  1013
 1   1:2  1013
 1   1:0  1013         END;
 1   1:8  1013       END;
 1   1:6  1013    END;
 1   1:6  1015
 1   1:5  1015    1: CASEOUT;
 1   1:5  1017       STATLOG;
 1   1:5  1019
 1   1:5  1019
 1   1:4  1019    END; (* CASE LOOP*)
 1   1:2  1026    END; (* ITERATION LOOP *)
 1   1:2  1033
 1   1:1  1033    STATOUT.
 1   1:1  1035
 1   1:1  1035
 1   1:1  1035    CLOSE(OUTPUT,LOCK);
 1   1:1  1044    RESET(OUTPUT,'CONSOLE:');
 1   1:1  1065    EXIT(PROGRAM);
 1   1:1  1069
 1   1:0  1069 END.
```

SAMPLE RUN

```
RAND STS RELIABILITY SIMULATION

     CASE TYPE 1 RUN 1
      9.95000E-1   4.50000E1   9.98500E-1     1.20000E2


          90%        91%        92%        93%        94%        95%        96%        97%        98%        99%       ·100%
     ---------!----------!----------!----------!----------!----------!----------!----------!----------!----------!---------!

     5    9.95735E-1
     10    9.96383E-1
     15    9.96944E-1
     20    9.97420E-1
     25    9.97809E-1
     30    9.98111E-1
     35    9.98327E-1
     40    9.98457E-1
     45    9.98500E-1
     50    9.98457E-1
     55    9.98327E-1
     60    9.98111E-1
     65    9.97809E-1
     70    9.97420E-1
     75    9.96944E-1
     80    9.96383E-1
     85    9.95735E-1
     90    9.95000E-1
     95    9.94179E-1
     100    9.93272E-1
     105    9.92278E-1
     110    9.91197E-1
     115    9.90031E-1
     120    9.88778E-1
     125    9.87438E-1
     130    9.86012E-1
     135    9.84500E-1
     140    9.82901E-1
     145    9.81216E-1
     -- ORBITER 4 RETIRED AT T=  9.55062E2 --
     -- ORBITER 3 RETIRED AT T=  9.57950E2 --
     -- ORBITER 2 RETIRED AT T=  9.59340E2 --
     -- ORBITER 1 RETIRED AT T=  9.62302E2 --
     MAXIMUM 480 MISSIONS AT T=  9.62302E2

      ORBITER  NO. OF FLIGHTS
     R 1          120
     R 2          120
     R 3          120
     R 4          120
     END CASE 1
```

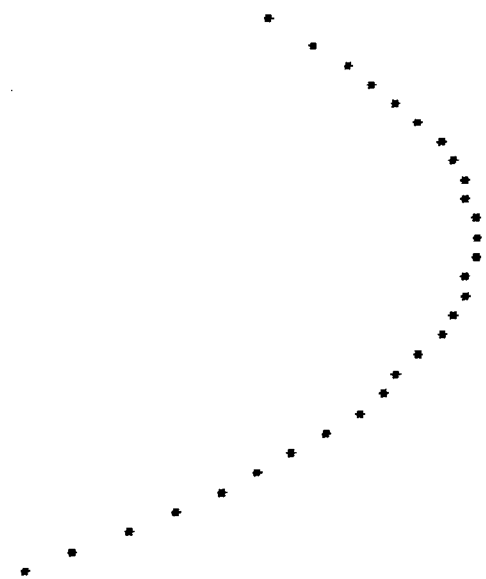


```
CASE TYPE 2 RUN 1
 9.90000E-1   6.00000E1   9.98000E-1     1.20000E2
```




```
5     9.91278E-1
10     9.92444E-1
15     9.93500E-1
20     9.94444E-1
25     9.95278E-1
30     9.96000E-1
35     9.96611E-1
40     9.97111E-1
45     9.97500E-1
50     9.97778E-1
55     9.97944E-1
60     9.98000E-1
65     9.97944E-1
70     9.97778E-1
75     9.97500E-1
80     9.97111E-1
85     9.96611E-1
90     9.96000E-1
95     9.95278E-1
100     9.94444E-1
105     9.93500E-1
110     9.92444E-1
115     9.91278E-1
120     9.90000E-1
125     9.88611E-1
130     9.87111E-1
135     9.85500E-1
140     9.83778E-1
145     9.81944E-1
** FAILURE, ORBITER 4 AT  T=  5.02024E1 **
** SUCCESSFUL ABORT **
** STANDOWN LENGTH: 37
** FAILURE, ORBITER 2 AT  T=  2.67465E2 **
** ORBITER LOST **
** STANDOWN LENGTH: 58
-- ORBITER 4 RETIRED AT T=  8.60131E2 --
-- ORBITER 3 RETIRED AT T=  8.62149E2 --
-- ORBITER 1 RETIRED AT T=  8.63377E2 --
ALL ORBITERS LOST OR RETIRED AT T=  8.64377E2
389 MISSIONS FLOWN

 ORBITER  NO. OF FLIGHTS
R 1         120
X 2         30
R 3         120
R 4         120
END CASE 2
```

```
CASE TYPE 3 RUN 1
 9.70000E-1   6.00000E1   9.90000E-1     1.20000E2

        90%       91%       92%       93%       94%       95%       96%       97%       98%       99%      100%
 ----------!---------!---------!---------!---------!---------!---------!---------!---------!---------!---------!
```



```
 5    9.73194E-1
10    9.76111E-1
15    9.78750E-1
20    9.81111E-1
25    9.83194E-1
30    9.85000E-1
35    9.86528E-1
40    9.87778E-1
45    9.88750E-1
50    9.89444E-1
55    9.89861E-1
60    9.90000E-1
65    9.89861E-1
70    9.89444E-1
75    9.88750E-1
80    9.87778E-1
85    9.86528E-1
90    9.85000E-1
95    9.83194E-1
100    9.81111E-1
105    9.78750E-1
110    9.76111E-1
115    9.73194E-1
120    9.70000E-1
125    9.66528E-1
130    9.62778E-1
135    9.58750E-1
140    9.54444E-1
145    9.49861E-1
** FAILURE, ORBITER 3 AT  T=  4.35243 **
** ORBITER LOST **
** STANDOWN LENGTH: 33
** FAILURE, ORBITER 4 AT  T=  1.41886E2 **
** ORBITER LOST **
** STANDOWN LENGTH: 36
** FAILURE, ORBITER 2 AT  T=  3.86638E2 **
** ORBITER LOST **
** STANDOWN LENGTH: 30
-- ORBITER 1 RETIRED AT T=  5.14671E2 --
ALL ORBITERS LOST OR RETIRED AT T=  5.15671E2
208 MISSIONS FLOWN

 ORBITER  NO. OF FLIGHTS
R 1          120
X 2          71
X 3          1
X 4          19
END CASE 3
```

```
CASE TYPE 4 RUN 1
 9.95000E-1   6.00000E1   9.98000E-1     1.20000E2

        90%        91%        92%        93%        94%        95%        96%        97%        98%        99%       100%
----------!----------!----------!----------!----------!----------!----------!----------!----------!----------!----------!

5    9.95479E-1
10     9.95917E-1
15     9.96312E-1
20     9.96667E-1
25     9.96979E-1
30     9.97250E-1


35     9.97479E-1
40     9.97667E-1
45     9.97812E-1
50     9.97917E-1
55     9.97979E-1
60     9.98000E-1
65     9.97979E-1
70     9.97917E-1
75     9.97812E-1
80     9.97667E-1
85     9.97479E-1
90     9.97250E-1
95     9.96979E-1
100     9.96667E-1
105     9.96312E-1
110     9.95917E-1
115     9.95479E-1
120     9.95000E-1
125     9.94479E-1
130     9.93917E-1
135     9.93312E-1
140     9.92667E-1
145     9.91979E-1
** FAILURE, ORBITER 2 AT  T=  1.16204E2 **
** ORBITER LOST **
** STANDOWN LENGTH: 35
** FAILURE, ORBITER 1 AT  T=  6.73158E2 **
** ORBITER LOST **
** STANDOWN LENGTH: 45
-- ORBITER 4 RETIRED AT T=  7.92528E2 --
-- ORBITER 3 RETIRED AT T=  7.94606E2 --
ALL ORBITERS LOST OR RETIRED AT T=  7.95606E2
354 MISSIONS FLOWN

 ORBITER  NO. OF FLIGHTS
X 1         101
X 2         15
R 3         120
R 4         120
END CASE 4
```

(Runs 2-49 not shown.)

```
CASE TYPE 1 RUN 50
 9.95000E-1   4.50000E1   9.98500E-1     1.20000E2


** FAILURE, ORBITER 2 AT  T=  7.32182E2 **
** ORBITER LOST **
** STANDOWN LENGTH: 32
-- ORBITER 4 RETIRED AT T=  9.35508E2 --
-- ORBITER 3 RETIRED AT T=  9.37044E2 --
-- ORBITER 1 RETIRED AT T=  9.39514E2 --
ALL ORBITERS LOST OR RETIRED AT T=  9.40514E2
450 MISSIONS FLOWN

 ORBITER  NO. OF FLIGHTS
R 1           120
X 2           91
R 3           120
R 4           120
END CASE 1



CASE TYPE 2 RUN 50
 9.90000E-1   6.00000E1   9.98000E-1     1.20000E2


** FAILURE, ORBITER 2 AT  T=  3.62421E2 **
** ORBITER LOST **
** STANDOWN LENGTH: 31
** FAILURE, ORBITER 1 AT  T=  3.95685E2 **
** ORBITER LOST **
** STANDOWN LENGTH: 49
-- ORBITER 4 RETIRED AT T=  7.43542E2 --
-- ORBITER 3 RETIRED AT T=  7.45830E2 --
ALL ORBITERS LOST OR RETIRED AT T=  7.46830E2
328 MISSIONS FLOWN

 ORBITER  NO. OF FLIGHTS
X 1           45
X 2           45
R 3           120
R 4           120
END CASE 2

 CASE TYPE 3 RUN 50
 9.70000E-1   6.00000E1   9.90000E-1     1.20000E2


** FAILURE, ORBITER 2 AT  T=  7.75850E1 **
** ORBITER LOST **
** STANDOWN LENGTH: 32
** FAILURE, ORBITER 3 AT  T=  2.05239E2 **
** ORBITER LOST **
** STANDOWN LENGTH: 31
** FAILURE, ORBITER 1 AT  T=  2.65333E2 **
** ORBITER LOST **
** STANDOWN LENGTH: 40
** FAILURE, ORBITER 4 AT  T=  3.63667E2 **
** ORBITER LOST **
** STANDOWN LENGTH: 30
ALL ORBITERS LOST OR RETIRED AT T=  3.64667E2
129 MISSIONS FLOWN

 ORBITER  NO. OF FLIGHTS
X 1           33
X 2           10
X 3           26
X 4           64
END CASE 3
```

```
CASE TYPE 4 RUN 50
 9.95000E-1   6.00000E1   9.98000E-1     1.20000E2


** FAILURE, ORBITER 3 AT  T=  1.48629E2 **
** ORBITER LOST **
** STANDOWN LENGTH: 35
** FAILURE, ORBITER 1 AT  T=  7.24413E2 **
** SUCCESSFUL ABORT **
** STANDOWN LENGTH: 41
-- ORBITER 4 RETIRED AT T=  8.25984E2 --
-- ORBITER 2 RETIRED AT T=  8.28663E2 --
-- ORBITER 1 RETIRED AT T=  8.30572E2 --
ALL ORBITERS LOST OR RETIRED AT T=  8.31072E2
379 MISSIONS FLOWN

 ORBITER  NO. OF FLIGHTS
R 1           120
R 2           120
X 3           20
R 4           120
END CASE 4


 STATISTICS FOR 50 RUNS
 CASES
TYPE   R(1)       M       R(M)        MAX.MISS
1  9.95000E-1  4.50000E1  9.98500E-1   1.20000E2
2  9.90000E-1  6.00000E1  9.98000E-1   1.20000E2
3  9.70000E-1  6.00000E1  9.90000E-1   1.20000E2
4  9.95000E-1  6.00000E1  9.98000E-1   1.20000E2

CASE       MISSIONS    TIME TO      ORBITERS     MISSIONS     MAX MSNS.
            FLOWN      COMPLETE       LOST       PER ORB.     PER ORB.

1        4.31580E2    9.32900E2    1.08000     1.08165E2    1.20000E2
          4.98455E1    9.36670E1    7.44043E-1    1.23364E1     0.00000

2        3.92840E2    8.65602E2    1.32000     9.85400E1    1.19640E2
          7.84144E1    1.28044E2    9.47417E-1    1.94079E1     2.52004

3        2.54020E2    6.74143E2    3.10000     6.42800E1    1.13500E2
          7.89854E1    1.74273E2    7.81025E-1    1.96214E1     1.37641E1

4        4.18180E2    8.91096E2    8.80000E-1    1.04765E2    1.20000E2
          6.68072E1    1.12644E2    8.15843E-1    1.65392E1     0.00000
```

APPENDIX C: SIMULATION OF OPERATIONS WITH HYPOTHETICAL TIME-VARYING RELIABILITIES

The flat reliability profiles used in the analysis are useful as calibration points in the infinite range of possible reliability curves for an orbiter. The effects of learning, which will improve the initial reliability of the system, and wearout, which will reduce, are not captured with a flat reliability profile.

This appendix shows the results of a series of simulations based on an extended mission model of 480 flights over a nine-year period, similar to the original NASA mission model, and shown in Fig. C-1. In the main body of this Note the reduced 312 flight mission model was used.

In order to include the effects of time-varying reliability, it was necessary to hypothesize some possible reliability profiles. As explained in Sec. II, these are highly uncertain and do not constitute a prediction or forecast in any sense of the words. They were chosen because they lie in a range that is plausible and where the model results are interesting, i.e., with much lower reliabilities very few missions are flown, with much higher reliabilities little or no degradation from perfect performance is observed.

TIME-VARYING RELIABILITY CURVES FOR USE WITH THE SIMULATION MODEL

A simulation analysis based on the lower bounds or even the mid-values of reliability shown in Figs. 1 and 2 of Sec. II would be very uninteresting. All the orbiters would be lost within the first few dozen missions in all cases. Thus, it was necessary to determine a

February 15, 1980

Assumes transfer of OV 102 to VAFB in May 1983		
Orbiter deliveries		FOF: 3-82
OV-102 3/79	OV-103 9/83	
OV-099 6/82	OV-104 12/84	

By STS element

		FY 1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	Total
KSC	Spacelab	—	2	3	6	6	7	8	10	10	10	10	10	10	92
	Upper stages	—	3	9	7	13	17	20	22	21	22	22	22	22	200
	Free-flyers	—	—	1	1	1	2	3	3	3	2	2	2	2	22
	Large structures	—	—	—	—	—	1	3	3	4	4	4	4	4	27
	Reflights	—	—	1	1	2	2	2	2	2	2	2	2	2	20
	Total KSC	—	**5**	**14**	**15**	**22**	**29**	**36**	**40**	**40**	**40**	**40**	**40**	**40**	**361**
VAFB	Spacelab	—	—	—	—	—	1	2	2	3	2	2	3	3	18
	Upper stages														
	Free-flyers	—	—	—	4	7	10	10	11	11	12	12	11	11	99
	Reflights	—	—	—	—	1	1	1	1	1	1	1	1	1	9
	Total VAFB	—	—	—	**4**	**8**	**12**	**13**	**14**	**15**	**15**	**15**	**15**	**15**	**126**
	Flight total	—	**5**	**14**	**19**	**30**	**41**	**49**	**54**	**55**	**55**	**55**	**55**	**55**	**487**

Traffic projection — for planning purposes only

Note: Only operational flights shown

Fig. C-1 — STS flight traffic baseline
(First operational flight in March 1982)

range of plausible reliability figures for an operational fleet of shuttles. It was postulated that an initial reliability would be substantially higher than the 95 percent figure seen in the expendable launch vehicle era. This initial reliability would then increase due to learning and increased sophistication as more and more missions were flown and minor problems corrected. The reliability would reach a maximum sometime during the orbiter's life and then decline as a result of wearout as the orbiter neared the end of its useful lifetime.

Four reliability curves with this general shape were postulated for use in the simulation analysis that follows. Each was specified by three parameters: the initial reliability, the highest reliability, and the number of missions at which the highest reliability occurs. Intermediate reliabilities for missions not at one of the three specified points were determined by fitting a quadratic curve that met the specified conditions. The parameters chosen for the four test cases, and calculated reliability at 120 missions, are shown in Table C-1. The curves generated using these parameters can be seen in Fig. C-2. Each of these cases represents a substantial improvement in reliability based on the past performance of expendable launch vehicles. The detailed calculation of intermediate points on these curves from the fixed conditions is explained in Appendix B.

These reliability figures are interpreted as before to mean the probability that no situation resulting in a fleet stand-down or the loss of an orbiter will occur. One minus the probability shown in these curves is the likelihood of a failure, which would result in either an abnormal recovery following a successful abort or the loss of an orbiter.

Table C-1

PARAMETERS USED TO ESTABLISH
HYPOTHETICAL SHUTTLE RELIABILITY PROFILES

Case	Reliability at First Mission	Maximum "Mature" Reliability	Number of Missions to Maximum Reliability	Reliability at 120 Missions
1	99.5%	99.85%	45	99.0%
2	99.0%	99.80%	60	99.0%
3	97.0%	99.00%	60	97.0%
4	99.5%	99.80%	60	99.5%

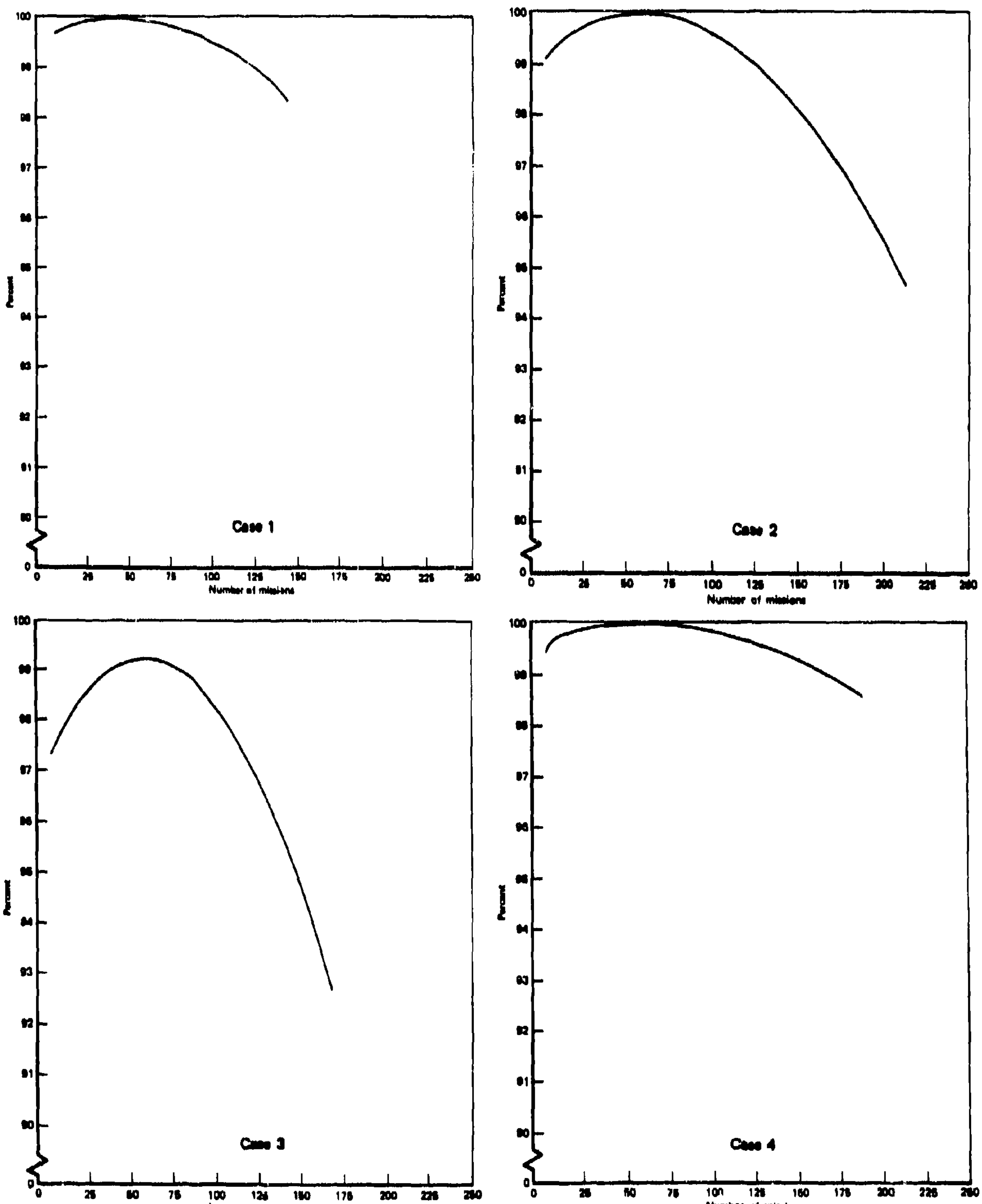


Fig. C-2 — Hypothetical time varying reliability profiles used in the simulation analysis

OTHER FACTORS AFFECTING SPACE TRANSPORATION SYSTEM OPERATIONS

While reliability is perhaps the most obvious and strongest uncertain factor having a major effect on STS operations, other uncertain aspects of equal or perhaps greater significance are the lifetimes of the individual orbiter vehicles and delays in turnaround time. Excessive shortfalls in either area will have a drastic effect on the overall launch capacity of the fleet.

Vehicle lifetimes are unknown and cannot be realistically estimated without data from a number of completed missions. One can observe, however, that there is a close link between the required vehicle lifetimes and the reliability of the individual orbiters. A hypothetical mission model based loosely on the NASA schedule (Fig. C-1) would consist of 480 missions flown at regular intervals over 10 years. Were no failures to occur, each orbiter would fly 120 missions at a rate of one per month for 120 months. This differs from the NASA model mainly in the uniformity of the schedule, but the overall differences do not have much impact on the results. However, since the reliability of the orbiters is uncertain and less than 100 percent, there is a possibility that one or more orbiters will be lost, thus requiring longer lifetimes for the remaining vehicles, or termination of launch activities without completion of all of the assigned missions.

Turnaround time delays, while not closely linked with reliability, do affect the flight rate in a major way. Turnaround delays have been extensively studied elsewhere [Ref. 2] and their effects are incorporated in the model described in the following section.

A third factor affecting the overall rate at which the fleet can operate is the length of a stand down following a failure. We can presume that a failure resulting in the loss of an orbiter will result in a longer stand-down period than one ending in a successful recovery following an abort. In most cases, it will take longer to fix four vehicles than one, so the length of a stand down will depend on the complexity of the modification or repair required and the number of orbiters on which it must be performed.

The manned nature of the orbiters makes this a particularly sensitive area. We apply extremely high standards to manned missions. The only examples we have to draw inferences from come from the Apollo program. The Apollo 204 test fire took the lives of astronauts Chaffee, Grissom, and White, and resulted in major changes in the Apollo life support systems during a 10 month stand down. A shorter delay of approximately five months followed the Apollo 13 failure, when an explosion in the service module of the Apollo capsule during the flight to the moon created an emergency which required abandoning the lunar landing attempt. Extensive cannibalization of the remaining equipment in the lunar module was needed to successfully recover the crew. Variable stand-down intervals reflecting the severity of the incident precipitating them are included in the simulation model described in the following section.

RESULTS OF THE SIMULATION ANALYSIS

We consider the simulated operation of a fleet of four shuttles assigned a "regularized" version of the NASA 487 flight traffic baseline of Fig. C-1. As stated previously, this consists of 480 missions flown over a 480 week period. If the shuttles have 100 percent reliability and experience no turnaround time delays, one flight will be launched each week, with the orbiters remaining in space for up to two weeks, landing, and being refurbished within the nominal two-week turnaround time. Thus, in this imaginary, perfect case, 480 missions will be flown in 480 weeks, with each orbiter flying 120 missions, and no orbiters lost due to accident. There would be no turnaround delays on the ground, no failures, and no stand-down periods.

We use this standard of comparison to evaluate the first of the simulation runs, which is the case where orbiters are not retired. If an orbiter is lost, it is assumed that the lifetime of the remaining orbiters can be extended to allow them to pick up the missions which would have otherwise been conducted by the missing orbiter or orbiters. Table C-2 shows the results of 50 runs for each of the four reliability profiles introduced in Fig. C-2. The entries in the table indicate the number of missions flown, the time to complete them, the range of orbiters lost (for the probabilities of loss in aborts between 0.2 and 0.8), the average number of missions per orbiter, and the maximum number of missions for a particular orbiter in each of the cases. The figures other than orbiter losses are based on a probability of loss following abort of 0.7. The table gives both the mean values for these parameters and their standard deviations in parentheses below the principal results. These figures show that in the three more optimistic cases (1, 2, and 4) it is reasonable to expect that something close to the nominal number of missions can be flown, though in a much longer period due to stand downs following accidents alone. These results do not include any delays d to extended turnaround time, but do include stand-down

Table C-2

NO ORBITER RETIREMENT, NO TURNAROUND DELAY

Reliability Case	Missions Flown	Time to Completion	Orbiters Lost	Range of Orbiters Lost	Average Missions Per Orbiter	Maximum Missions Per Orbiter
1	462 (41)	549 (53)	1.8 (1.5)	0.5-2.1	116 (10)	149 (31)
2	456 (57)	542 (61)	1.7 (1.5)	0.5-1.9	114 (14)	149 (34)
3	238 (108)	422 (150)	4.0 (0)	1.1-4.0	61 (27)	119 (42)
4	476 (17)	545 (49)	1.1 (1.1)	0.3-1.3	119 (4)	145 (26)

NOTE: For this table and all others of this type, unless otherwise noted, the number of runs for each case is 50. Figures in parentheses are standard deviations. For all figures other than the range of orbiters lost, the numbers shown are based on probability of loss after abort of 0.7.

periods. Averaged over the 50 runs in the more optimistic cases, between one and two orbiters were lost to accidents. In the least optimistic case, Case 3, all four orbiters were lost in each of 50 simulations. It should be noted, however, that the mean maximum number of missions required of the orbiter with the most service in each case is close to 150 for the three high-reliability cases. These average figures do not reflect the extreme values. In some cases, close to 200 missions are required of an orbiter if the others fail early in the simulation period.

EFFECTS OF ORBITER RETIREMENT

Table C-3 shows the equivalent results for 50 runs for each of the four reliability cases under the condition that each orbiter is retired after flying 120 missions. It can be seen that a far smaller number of missions are flown in a shorter time; the number of orbiters lost is also somewhat reduced. This is because fewer missions are flown in the low reliability region beyond 120 missions. The shorter times to completion reflect the lower number of missions actually flown. The increases in time to completion over the nominal values of one week per mission are due entirely to stand downs, since no turnaround delays were included in this series of runs.

It is conceivable that operating experience will require that orbiters be retired before 120 missions. If this occurs there is no way for a four-orbiter fleet to fly all 480 missions. For instance, if

Table C-3

ORBITER RETIREMENT AFTER 120 MISSIONS, NO TURNAROUND DELAY

Reliability Case	Missions Flown	Time to Completion	Orbiters Lost	Range of Orbiters Lost	Average Missions Per Orbiter	Maximum Missions Per Orbiter
1	412 (56)	481 (49)	1.3 (0.9)	0.4-1.5	103 (14)	120 (0)
2	379 (96)	461 (72)	1.5 (1.1)	0.4-1.7	95 (24)	119 (6)
3	254 (101)	415 (112)	3.0 (0.8)	0.9-3.4	64 (25)	108 (24)
4	437 (54)	481 (36)	0.7 (0.8)	0.2-0.8	109 (14)	120 (0)

orbiters must be retired after 80 missions, then a maximum of only 320 missions can be flown. This maximum will not be reached, however, since early-retiring orbiters are subject to the same reliability problems that affect the other cases. Tables C-4 and C-5 show results for orbiter retirement at 100 and 80 missions, respectively.

We can summarize these results with Fig. C-3, which shows the effects found with the simulation regarding different orbiter retirement procedures. Points appearing below the 480 mission line and to the right of the 480 week line represent fleet histories with fewer than the nominal number of missions flown, in more than the nominal time.

Another way of looking at these results is seen in Fig. C-4, which shows the mission weighted flight rates for each case. The mission weighted flight rate is determined simply by dividing the number of

Table C-4

ORBITER RETIREMENT AFTER 100 MISSIONS, NO TURNAROUND DELAY

Reliability Case	Missions Flown	Time to Completion	Orbiters Lost	Range of Orbiters Lost	Average Missions Per Orbiter	Maximum Missions Per Orbiter
1	371 (37)	411 (24)	0.7 (0.6)	0.2-0.8	93 (9)	100 (0)
2	338 (68)	396 (46)	0.9 (0.9)	0.3-1.0	85 (17)	99 (5)
3	229 (72)	383 (82)	2.7 (0.9)	0.8-3.1	58 (18)	94 (18)
4	366 (41)	409 (31)	0.6 (0.7)	0.2-0.7	92 (10)	100 (0)

Table C-5

ORBITER RETIREMENT AFTER 80 MISSIONS, NO TURNAROUND DELAY

Reliability Case	Missions Flown	Time to Completion	Orbiters Lost	Range of Orbiters Lost	Average Missions Per Orbiter	Maximum Missions Per Orbiter
1	295 (40)	328 (26)	0.5 (0.8)	0.1-0.6	74 (10)	80 (0)
2	277 (45)	324 (32)	0.8 (0.8)	0.2-0.9	69 (11)	80 (0)
3	195 (59)	332 (64)	2.4 (1.0)	0.7-2.7	49 (15)	77 (9)
4	294 (30)	332 (23)	0.6 (0.6)	0.2-0.7	74 (7)	80 (0)

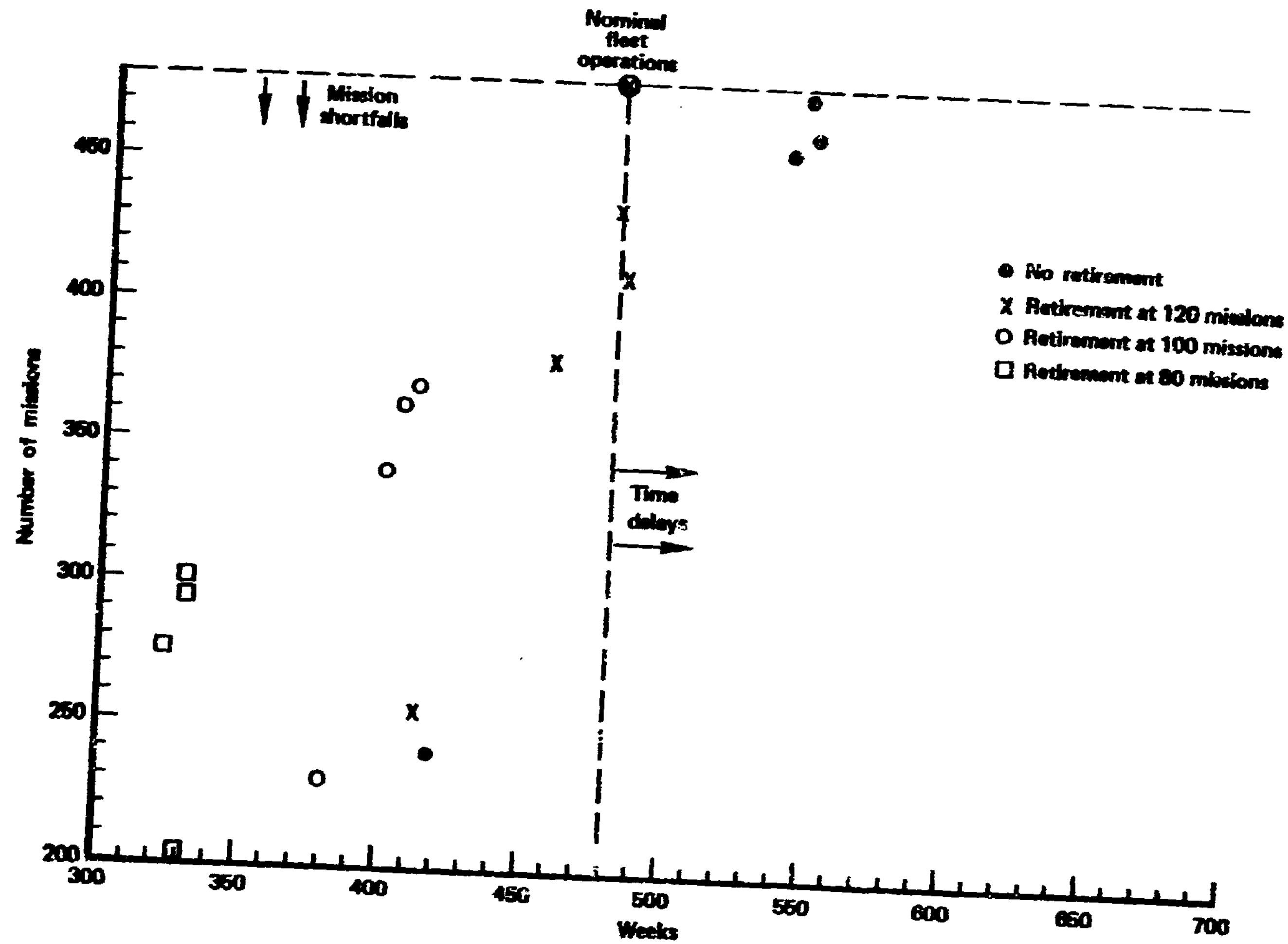


Fig. C-3 — Effects of orbiter retirement (no turnaround delays)

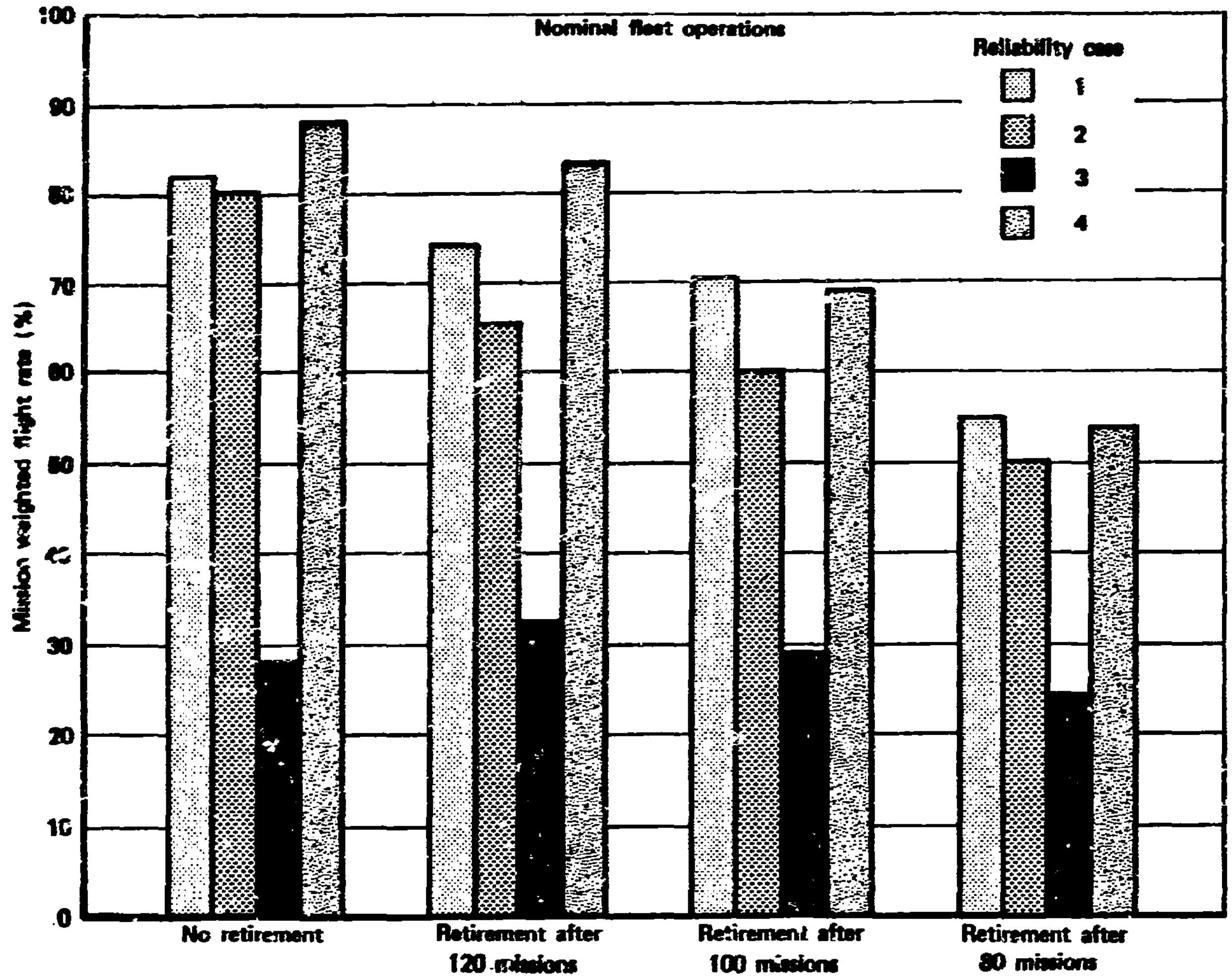


Fig. C-4 —Effects of orbiter retirement on STS fleet performance (no turnaround delays) missions flown by the time to completion, then multiplying the result by the fraction of the 480 assigned missions actually flown. The reason for using the mission weighting instead of the actual flight rate is to avoid erroneous comparisons. If the unweighted flight rate (the number of missions divided by the time to completion) was used, four successful flights in four weeks followed by four crashes would result in an unweighted flight rate of 100 percent, as would 480 flights in sequence with no delays. It is useful to distinguish between these widely varying outcomes.

All of these cases are unrealistic in the sense that no turnaround delays are involved. Introduction of this factor will not change the total number of missions flown, but it will spread them out over a longer time, as will be seen below.

Figure C-4 shows the mission weighted flight rates for the different orbiter retirement policies. They range from a high of 87 percent for a high reliability, no retirement case down to 24 percent for retirement after 80 missions and under the most "pessimistic" reliability assumptions (those between 97 percent to 99 percent). Any simulation with reliabilities significantly lower than this range results in abysmally poor fleet performance, below 10 percent on the scale used here.

TURNAROUND TIME DELAYS

Allowing an increase in average turnaround time of 15 percent for each orbiter yields the results shown in Table C-6. As expected, the number of missions flown is comparable, as are the number of orbiters lost, the missions per orbiter, and the maximum missions per orbiter.

All are within the normal expected statistical variation. The principal differences noted are the times to complete the sequence of missions. Tables C-7, C-8, C-9, and C-10 show the results for delays of 30, 45, 60, and 100 percent, with retirement of the orbiters at 120 missions. These are perhaps more realistic cases than we have discussed so far. We can compare these cases by looking at the flight rate, i.e., the number of missions per week. These results are shown in the two-dimensional plot of Fig. C-5, which indicates the magnitude of the expected mission shortfalls and time delays. Figure C-6 shows the mission weighted flight rates for turnaround time delays ranging from 15 to 100 percent. The weighted flight rates range from a high of 69 percent down to 20 percent in the worst example shown. These figures all assume orbiter retirement after 120 missions.

Table C-6

AVERAGE TURNAROUND DELAY OF 15 PERCENT,
RETIREMENT AFTER 120 MISSIONS

Reliability Case	Missions Flown	Time to Completion	Orbiters Lost	Range of Orbiters Lost	Average Missions Per Orbiter	Maximum Missions Per Orbiter
1	431 (57)	562 (53)	1.0 (0.8)	0.3-1.1	108 (14)	120 (0)
2	403 (71)	549 (83)	1.4 (1.0)	0.4-1.6	101 (18)	120 (0)
3	246 (94)	449 (127)	3.2 (0.8)	0.9-3.7	62 (23)	108 (24)
4	420 (81)	540 (68)	0.9 (1.0)	0.3-1.0	105 (20)	119 (9)

Table C-7

AVERAGE TURNAROUND DELAY OF 30 PERCENT,
RETIREMENT AFTER 120 MISSIONS

Reliability Case	Missions Flown	Time to Completion	Orbiters Lost	Range of Orbiters Lost	Average Missions Per Orbiter	Maximum Missions Per Orbiter
1	416 (63)	610 (74)	1.1 (0.8)	0.3-1.3	104 (16)	120 (0)
2	384 (74)	576 (75)	1.3 (0.9)	0.4-1.5	96 (18)	120 (0)
3	240 (83)	486 (132)	3.2 (0.8)	0.9-3.7	61 (21)	108 (23)
4	450 (41)	648 (52)	0.7 (0.7)	0.2-0.8	113 (10)	120 (0)

Table C-8

AVERAGE TURNAROUND DELAY OF 45 PERCENT,
RETIREMENT AFTER 120 MISSIONS

Reliability Case	Missions Flown	Time to Completion	Orbiters Lost	Range of Orbiters Lost	Average Missions Per Orbiter	Maximum Missions Per Orbiter
1	433 (53)	697 (63)	1.2 (1.0)	0.3-1.4	108 (13)	120 (0)
2	384 (81)	642 (98)	1.4 (0.9)	0.4-1.6	96 (20)	119 (4)
3	250 (91)	519 (148)	3.1 (0.9)	0.9-3.5	63 (22)	108 (23)
4	438 (58)	684 (67)	0.7 (0.7)	0.2-0.8	110 (14)	120 (0)

Table C-9

AVERAGE TURNAROUND DELAY OF 60 PERCENT,
RETIREMENT AFTER 120 MISSIONS

Reliability Case	Missions Flown	Time to Completion	Orbiters Lost	Range of Orbiters Lost	Average Missions Per Orbiter	Maximum Missions Per Orbiter
1	422 (69)	740 (94)	1.1 (0.8)	0.3-1.3	106 (17)	120 (0)
2	397 (71)	706 (88)	1.2 (0.9)	0.3-1.4	99 (18)	120 (0)
3	245 (91)	567 (165)	3.0 (0.7)	0.9-3.4	62 (23)	108 (25)
4	431 (54)	751 (72)	0.8 (0.8)	0.2-0.9	108 (13)	120 (0)

Table C-10

AVERAGE TURNAROUND DELAY OF 100 PERCENT,
RETIREMENT AFTER 120 MISSIONS

Reliability Case	Missions Flown	Time to Completion	Orbiters Lost	Range of Orbiters Lost	Average Missions Per Orbiter	Maximum Missions Per Orbiter
1	432 (50)	941 (92)	1.1 (0.9)	0.3-1.3	108 (12)	120 (2)
2	390 (79)	854 (142)	1.3 (0.8)	0.4-1.5	98 (20)	120 (0)
3	260 (87)	690 (188)	3.1 (0.7)	0.9-3.5	66 (22)	112 (17)
4	417 (58)	897 (102)	0.9 (0.8)	0.3-1.0	104 (14)	120 (0)

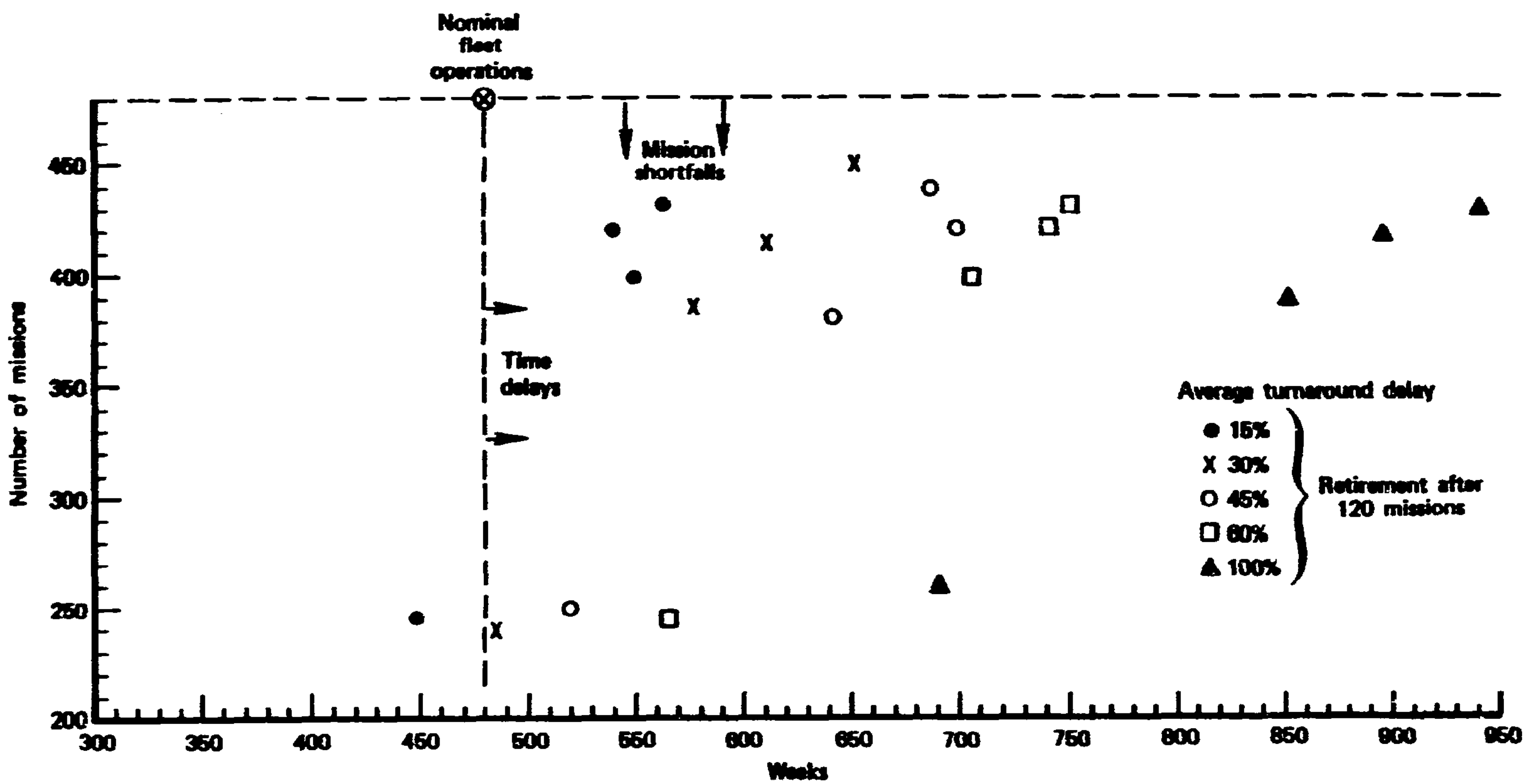


Fig. C-5 — Effects of turnaround time delays

COMBINED EARLY RETIREMENT AND TURNAROUND DELAYS

To demonstrate the full combination of all the orbiter retirement and turnaround delay scenarios considered so far would be extremely tedious and not especially illuminating. Instead, one case, with the least favorable set of conditions, was run. In this situation, orbiters are retired after 80 flights and turnaround delays average 100 percent. The results are seen in Table C-11. The mission weighted flight rates for these cases are between 14 and 30 percent.

This is not meant to imply that turnaround delays will never exceed 100 percent or that orbiter lifetimes will be at least 80 missions. Only years of experience can answer these questions.

Table C-11

AVERAGE TURNAROUND DELAY OF 100 PERCENT,
RETIREMENT AFTER 80 MISSIONS

Reliability Case	Missions Flown	Time to Completion	Orbiters Lost	Range of Orbiters Lost	Average Missions Per Orbiter	Maximum Missions Per Orbiter
1	303 (27)	638 (44)	0.4 (0.6)	0.4-0.5	76 (7)	80 (0)
2	278 (51)	604 (76)	0.8 (0.8)	0.8-0.9	70 (13)	80 (0)
3	182 (76)	499 (146)	2.4 (1.2)	2.4-2.7	46 (19)	72 (17)
4	288 (47)	613 (71)	0.6 (0.7)	0.6-0.7	72 (12)	80 (0)

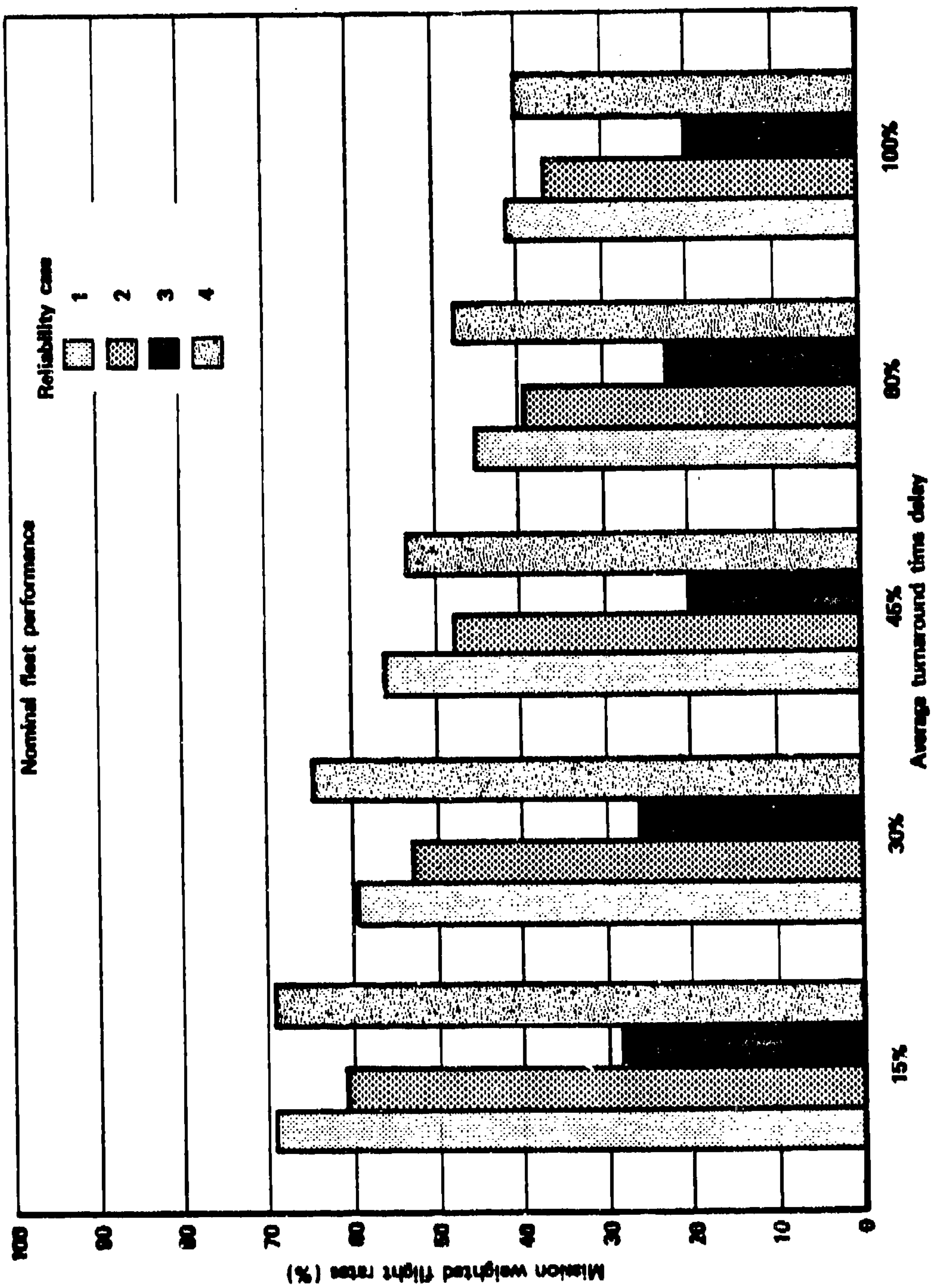


Fig. C-8—Effects of turnaround time delays on STS fleet performance (orbiter retirement after 120 missions)

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